



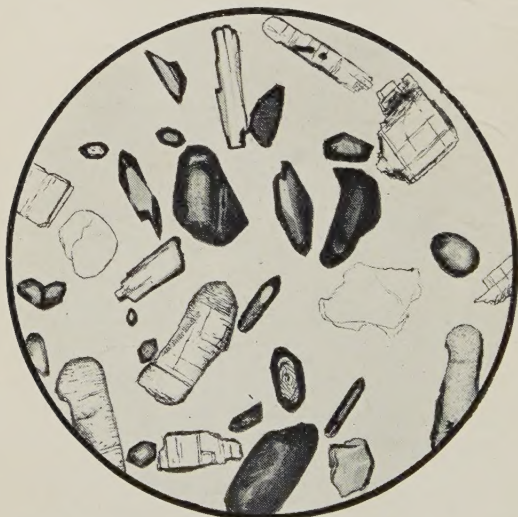
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MINERALS FROM ASPHALTIC SANDSTONE, ANGOLA.

A. Magnetic Separation. Ilmenite, Tourmaline and Garnet. [x 50.]

B. Non-magnetic Separation. Rutile, Zircon, Sillimanite, Kyanite
Muscovite. [x 50.]

Frontispiece.]

SEDIMENTARY PETROGRAPHY

With special reference to
Petrographic Methods of Correlation of Strata
and to
Subsurface Oil Geology

By

HENRY B. MILNER

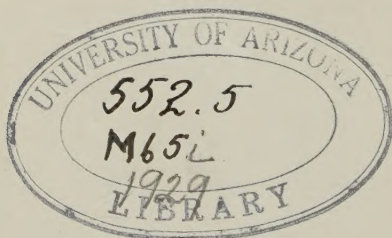
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2nd (Revised and Complete) Edition.

LONDON: THOMAS MURBY & CO., 1, FLEET LANE, E.C.4
NEW YORK: D. VAN NOSTRAND CO., 250, FOURTH AVENUE
1929.

<i>Introduction to Sedimentary Petrography first published</i>	-	1922
<i>Supplement published</i>	- - - - -	1926
<i>Introduction reprinted</i>	- - - - -	1927
<i>Second (complete and enlarged) Edition</i>	- - - - -	1929



PRINTED IN GREAT BRITAIN
 BY
 THE WOODBRIDGE PRESS, LTD.
 GUILDFORD.

PREFACE TO THE SECOND EDITION.

This edition embodies certain sections of the original volume (1922), much of the supplement (1926)—both subjected to critical revision—and a great deal of new matter. The blending of these data has compelled an entire rearrangement of text, now divided into eleven distinct chapters with three appendices.

The aim is not only to bring the whole work up-to-date, but to enlarge its scope in providing a comprehensive text-book of petrology of sediments, both incoherent and consolidated. As before, the impetus universally accorded to detailed studies of sedimentary rocks by the exigencies of oilfield developments is the excuse, if such be necessary, for biasing the work in this direction; but it is believed that such bias, far from being detrimental to the wider use of the volume, should, by focussing attention to detail thus implied, considerably enhance its value in the hands of all investigators of sedimentary deposits, whether in academic or other spheres of interest.

Regarding the new material, additions are made to the introduction, discussions on samples, storage and records, also in connexion with laboratory technique (Chs. I-III), in keeping with modern ideas and practice. Two new chapters ensue (IV and V), one devoted to the microscope, its role in this particular research, and especially its function in the provision of optical measurements; the other, to quantitative aspects of the subject, wherein there is still room for substantial advancement of knowledge. In the chapter on diagnostic properties of sedimentary rock-minerals (VI), columbite, diamond, euclase, gold and wolframite have been omitted in favour of their more

logical treatment as alluvial species elsewhere; in their place, anhydrite, aragonite, celestite and spodumene are described; additionally, twenty-five sporadically occurring minerals in sediments are briefly noted, each with appropriate references to records. It will be found that essential, especially optical, properties of those minerals discussed in detail, have been considerably expanded, the desire being to give the fullest and most varied data leading in each case to positive diagnosis; the practice of noting specific occurrences and records by different authors, first adopted in the supplement, has been continued, and includes relevant references to the literature.

Chapter VII on consolidated rocks is the chief departure from original plan. In this, an attempt is made to describe systematically every familiar type on the basis of logical classification. While it is not for one moment contended that the system is inviolable, the author feels that, if adhered to in principle, it has the merit of fixing regard to essential characters of these rocks, textural, mechanical, mineralogical and structural. These features constitute the cumulative evidence by which they should be classified, described and known, and by which, in thin section, they may suffer comparison for purposes of correlation or differentiation in oilfield technology or in other circumstances. It will be observed that pyroclastic rocks, often included in petrological considerations of sediments, find no mention in this book. This is intentional, since the author holds the view that their study is impossible without collateral description of volcanic igneous types; to gain such an end, trespass into the domain of igneous petrology is inevitable, a step definitely negatived by the title and scope of this work. Reconstituted sediments, *e.g.*, slate, phyllite, implying thermal or dynamic stress (or both) for their production, are excluded for similar reasons.

Both principles and practice of correlation and differentiation of sediments, either by heavy minerals

or by thin sections, have been restated in the light of more extensive experience, especially in connexion with subsurface (exploitation) oil-geology. In rewriting this section, the endeavour has been made to keep an even balance between precept and method, to emphasize equally potentialities and limitations. A schedule of indispensable data for these applications, fully annotated, has been drawn up as a guide in routine work. Actual examples of correlation and differentiation of sediments by international workers are quoted in Chapter IX, substantially as published in the supplement, while several additions to the more theoretical bearings of the subject, palæogeography and geochemical significance of minerals, are made in Chapter X.

The increasing activities of investigators of soils and related superficial deposits at research stations at home and abroad, the repeated calls for further petrological evidence in this science of "pedology," and the advisability of clearing the ground for co-operative work by the several interests involved, are reasons for inclusion of a chapter on the applications of sedimentary petrography in this connexion. A considerable amount of purely mineralogical data has already been published, though often with somewhat conflicting ends in view. The time seems ripe for an exposition of the petrological standpoint, and it is hoped that the discussion in Chapter XI will prove of value to agricultural chemists, physicists and mineralogists for whom soil investigations make common cause.

Numerous alterations and additions have been made to the illustrations. Of the 72 minerals fully described, 55 are figured; 70 photomicrographs of thin sections of typical rocks (apart from text-figures) are included; these, with various diagrams and photomicrographs of mineral assemblages, raise the total to 181, or more than double the number appearing in the previous volumes.

Thanks are due to the Governing Body of the Imperial College of Science, through the good offices of Prof. W. W. Watts, F.R.S., for permission to use, as a basis of illustration, many rocks and microscope-preparations in the collection of the Geological Department; to the Councils of the Royal Microscopical Society and Geologists' Association for permission to reproduce *figs.* 4, 7, and 20, 28, 29, 31, 40, 74 respectively, the six latter from Dr. A. Brammall's valuable paper on "Dartmoor Detritals"; to the Director of the Geological Survey of Nigeria for sanction to copy *figs.* 136 and 137 from Bull. 7 by Dr. W. Russ; to Mrs. C. Raeburn for her skilful execution of *figs.* 117, 136, 137, 156, 161, 162 and 181; to Dr. C. Raeburn for help with certain diagrams and his agreement to reproduction of eleven text-figures from "Alluvial Prospecting"; to Dr. F. Smithson for drawing *figs.* 48 (4-7) gypsum, and 67, spodumene; to Mr. E. F. Newton for his drawings of titanite (*fig.* 69); to Dr. A. W. Groves for his original photographs of dumortierite (*fig.* 39); to the Anglo-Persian Oil Co., Ltd., for permission to illustrate anhydrite grains (*fig.* 22) from rocks submitted by their Geological Department; and to Messrs. J. Swift and Son for the loan of blocks of *figs.* 8 and 9. Other illustrations reproduced from the original volume and supplement, largely the work of Messrs. G. M. Part and G. S. Sweeting, receive due acknowledgment elsewhere (pp. xi, xiii).

For permission to use certain rocks and slides in their collections, the author gratefully records the kindness of his colleagues, Prof. W. W. Watts, F.R.S., Prof. C. G. Cullis, Prof. A. Morley Davies, Prof. V. C. Illing and Dr. A. Brammall. The loan of a large collection of microscope slides of sedimentary rocks from Mr. G. M. Part contributed much both to discussion of types and to illustration. Also, by his skilful preparation of thin sections of clays, coals, asphalts and other difficult rocks, Mr. E. J. Tallin, of the Geological Department of the Imperial College,

greatly facilitated description and selection of types for illustration.

The proofing of a book of this kind, in which so much technical detail figures prominently, is an onerous task, and the author has been fortunate in the generous assistance received from many friends. His thanks are specially tendered to Mrs. C. Raeburn for her invaluable help in this connexion; to Prof. P. G. H. Boswell for his critical reading of the text and for many helpful suggestions duly embodied; to his colleague, Dr. A. Brammall, for a similar courtesy in connexion with Chapters IV and VI; also to Messrs. J. N. Montgomery and M. H. Lowson for checking the mineral data and much of the detail of Chapters VI and VII, and for their help, in company with Mr. R. C. Jennings, with the preparation of the bibliography.

Finally, as on many previous occasions, the author gladly records his indebtedness and thanks for the valued co-operation of Mr. G. S. Sweeting, who is responsible for all the photomicrographs in the book, for reading the proofs at every stage of its progress through the press, and for his compilation of the index.

To Mr. G. H. Freeman (T. Murby & Co.), is due that acknowledgment of cordial relationship and sympathy between publisher and author, from which a successful literary production alone can spring.

H. B. MILNER.

IMPERIAL COLLEGE OF SCIENCE
AND TECHNOLOGY, LONDON,
April, 1929.

PREFACE TO FIRST EDITION.

This book has been designed to meet the requirements of all those engaged in the study of microscopical examination of sediments—more especially incoherent detrital deposits—whether for academic or economic purpose. The plan adopted is much the same as that forming the basis of a course of lectures in Sedimentary Petrography (as applied to Oil Technology) given by the author at the Royal School of Mines, and as many of the methods involved are new, not in principle but in application, it is thought that a useful purpose may be served by presenting them in a concise form to a larger audience.

The application of Sedimentary Petrography to certain branches of pure and economic geology, the gradual evolution of the higher technique involved, and the parts played by British geologists in laying the foundations of the subject, are sufficiently discussed in the Introduction which follows, rendering further remarks in connexion therewith unnecessary. At the outset, however, it is desirable to emphasize the fact that, as with other branches of natural science and their technical applications, no degree of finality can be said to have been achieved, and an enormous amount of research, both in the field and in the laboratory, awaits prosecution.

Petrographic methods as means of correlating loose detrital sediments (with which this volume is largely concerned), constitute a factor of the greatest possible import in practical geology. While it has been the author's aim to present this application both in principle and in method, it has been equally his duty to indicate, partly directly and partly by inference, the

wider potentialities of the subject and the trend of ultimate inquiries likely to lead to far-reaching results, both from the purely scientific and from the economic points of view.

As its title implies, the book is intended to serve simply as a general introduction to the subject and its applications. A working knowledge of elementary crystallography and optical physics is assumed, this being an essential preliminary to all petrographical studies. In this connexion such standard works as Dana's "System of Mineralogy" or Iddings' "Rock Minerals" should, if necessary, be consulted.

The author desires to record his indebtedness and thanks to his friend, Mr. G. M. Part, M.A., F.G.S., for undertaking the arduous task of reproducing the many detrital mineral grains and diagrams embodied in the book. Mr. Part not only made himself responsible for all the illustrations, but he assisted the author very considerably in the difficult task of selecting the most representative grains for reproduction.

To Dr. H. H. Thomas, Sc.D., V.P.G.S., the author's thanks are due for the loan of and permission to reproduce grains from the hypersthene concentrate from Santa Cruz (*fig. 12*) and the magnetite, etc., from Hinksford, Staffs (*fig. 16*), the latter originally described by Mr. J. B. Scrivenor, M.A., F.G.S. [*Min. Mag.*, vol. xiii., p. 351].

The author's thanks are also due to Mr. A. Brammall, M.Sc., D.I.C., F.G.S., for kindly reading the proofs of Chapter II and for presenting the material from which certain anatase grains were drawn (*fig. 2*).

Finally, to Mr. G. S. Sweeting, Royal School of Mines, for reading the proofs, indexing and many valuable suggestions, and to Mr. G. H. Freeman (Messrs. T. Murby & Co.) for the painstaking care with which he guided the book through the press, the author tenders his grateful thanks.

AUTHOR'S NOTE TO SUPPLEMENT (1926).

The Petrology of Sedimentary Rocks—particularly the study of detrital minerals—has developed rapidly in the last few years, due in no small measure to a wider appreciation of its applications to petroleum geology and also to a steadily increasing international body of students attracted both by its academic and economic possibilities.

The approaching exhaustion of the first issue of this book has for some months past compelled the author's attention to revision of the text for a second edition. When this came to be written, however, it was found that accumulated data constituted matter of dimensions such that its inclusion with the revised original text would result in the production of a volume double the size of the first edition and, at present costs, double the price. In view of this, it was felt that an opportunity should be afforded to those possessing the original volume to acquire the additional text and illustrations without the necessity of repurchasing much of the original subject-matter, and after careful consideration the publishers adopted this policy; hence the appearance of a "Supplement" at this juncture. Ultimately a revised second edition will incorporate this supplementary matter, together with any new data to hand in the interim, thus affording further opportunity for bringing the work up-to-date, an essential factor with a growing science.

This Supplement contains much that is new in technique and made known since 1922; additionally twenty minerals are described and twenty-eight species

figured, chiefly from material only recently available. Some of the figures illustrate minerals described in the main volume, others refer to species here discussed; taken together, over 50 distinct detrital minerals are now illustrated in the two volumes, while 74 species are described. As before, the author acknowledges his great indebtedness to Mr. G. M. Part, M.A., for his skilful execution of the wash-drawings from which the individual grains are reproduced. The difficulty of illustrating detrital minerals is known to all workers in this subject, and the author feels himself doubly fortunate in having the expert co-operation of Mr. Part and also of Mr. G. S. Sweeting, F.G.S., who is responsible for all the photomicrographs.

In response to several requests, a selection has been made of actual examples of stratigraphical differentiation and correlation by "heavy" minerals achieved by independent workers, as a guide to the technique of this application (Ch. IIIA). The theoretical phases of the subject receive stress from a geo-chemical consideration of detrital species as potential indicators of environment (Ch. IVA), and is intended to be suggestive. Also, a series of detrital mineral determination-tables has been devised whereby it is hoped that diagnosis in difficult cases will be facilitated.

The author gratefully acknowledges the help and suggestions of many friends both at home and abroad. His special thanks are due to his colleagues, Dr. A. Brammall, M.Sc., D.I.C., for his critical reading of Chapters IIA and IVA, and Mr. F. T. Ingham, B.Sc., for useful suggestions and the loan of special concentrates. To Messrs. W. F. Fleet, M.Sc., M. P. Latter, B.A., and S. W. Wooldridge, M.Sc., he is also indebted for the loan of slides containing good apatite, dolomite and chialstolite grains respectively. Mr. D. A. Greig, of the Royal School of Mines, kindly supplied the photographs from which *figs.* 34 and 35 are reproduced. Thanks are due to the Council of the

Royal Microscopical Society for the loan of a block for *fig. 36* (*Journ. Roy. Micros. Soc.*, vol. for 1924, p. 36); also to Messrs. J. Swift and Son, London, W.1, for a like courtesy (*fig. 37*).

The author finally records his grateful appreciation of the help of Mr. G. S. Sweeting in the further capacity of proof-reading, indexing and final responsibility of seeing this Supplement through the press, owing to the author's absence abroad. In this is included Mr. G. H. Freeman (Messrs. T. Murby and Co.), whose constant co-operation has been materially responsible for the success of the first volume and for the inception of this Supplement.

H. B. MILNER.

IMPERIAL COLLEGE OF SCIENCE
AND TECHNOLOGY, LONDON,
July, 1926.

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SEDIMENTARY PETROGRAPHY

CHAPTER I.

INTRODUCTION TO THE STUDY OF SEDIMENTARY ROCKS.

The intensive study of sedimentary petrography is a comparatively recent development of geological science, and one capable of playing an important rôle in stratigraphical research. This branch of natural science claims attention not only on account of an obvious academic value, but because its application to many phases of economic geology has been sought and perfected.

The principles and methods involved are peculiarly apposite to the more practical aspects of oilfield development where, for example, correlation of subterranean strata has frequently to be made entirely on the strength of the slender evidence afforded by well-sampling. More and more as new petroliferous areas are opened up are the claims of sound geological investigation of properties being recognized, and just as the application of microscopy has proved an invaluable asset to many branches of industrial geology, so is it fast becoming an important factor in modern oilfield development.

The study of microscopical organisms—chiefly *foraminifera*—in petroliferous deposits, has during the last few years been carried on assiduously in

many of the Tertiary oilfields of the world. It was hoped by this means to formulate a basis of identification and correlation of oil sands and their enclosing strata, thus providing results at once stratigraphically and structurally significant. Largely owing to the tendency of many of these organisms to have a wide distribution in space and time, the results, in so far as correlation within narrow limits is concerned, have not been universally encouraging, as at first anticipated. Nevertheless, some important stratigraphical data have been obtained in this way from rocks either poor in the larger and more easily recognizable fossils, or, if fossiliferous, in cases where the drilling system employed has inhibited, by comminution of the shells, their preservation in the well-samples. In these circumstances a comprehensive study of the mineralogical composition of the deposits with which oil is associated, offers, from first principles, great practical possibilities, and it is but a step to adapt the purely academic study of sedimentary petrography to the technical requirements in view.

The work of Professor V. C. Illing, in Trinidad, in 1915 and subsequently, clearly showed the great economic value attaching to a detailed petrological study of the highly disturbed oil-bearing strata in the southern part of the island; his recognition of successive groups of sediments characterized by exclusive mineral assemblages constituted a new weapon of attack on problems of correlation which had hitherto defied solution, and thus laid the foundation of this particular application of petrographic methods to stratigraphical analysis.

More recently, the author's researches on the correlation of isolated Tertiary deposits in Western Cornwall, on Wealden sediments and other British

formations, also on many well-samples from oil-fields in different parts of the world, have sustained the validity and value of the methods, especially where other means of differentiating between sediments are lacking. The work of many other investigators on similar lines, at home and abroad (of which a résumé is given in Chapter IX), has likewise proved both suggestive and conclusive.

In another direction, this applied petrology has furnished some important information with regard to the types of sand best suited to glass-making, foundry work, building purposes, etc. In this application Professor P. G. H. Boswell has, by his detailed studies of the sedimentary rocks in this country and in America, given us results of the utmost industrial import, and future work along these lines may be expected to aid the solution of many of the problems involved in the widespread use of refractories in the arts, especially in cases where difficulties are being constantly met with as a result of the adoption of purely empirical processes. This phase of study comprises not merely mineralogical, but chemical and mechanical analysis, and estimations of the degrees of permeability and porosity of the sediment; these factors have, incidentally, a special significance for the petroleum geologist and engineer.

The application of the subject to Alluvial Mining was indicated by the author in a paper published in 1923,¹ and has since been made the theme of a separate exposition in conjunction with C. Raeburn of the Geological Survey of Nigeria.² This phase of "Sedimentary Mineralogy," as it has been aptly termed by Professor A. Holmes, is both in principle and practice but a logical outcome

¹ H. B. Milner, *Mining Magazine*, xxviii., 1923, pp. 80-92.

² "Alluvial Prospecting," Murby, London, 1927.

of the comprehensive study of sediments, whether recent or ancient, and the particular technique implied is now influencing developments of alluvial deposits in different parts of the world. Quite apart from its economic bearing, the investigation of alluvial "heavy" minerals is of the greatest possible value—incidentally a most fascinating pursuit—in all problems of detrital mineralogy.

On the purely academic side, the tendency was at first towards research in the subject for its own sake, with little or no regard for its broader possibilities; the sampling of a particular sediment, the segregation of its "heavier" and more stable constituents and their ultimate mineralogical analysis, formed a welcome change from the investigation of thin sections of more compact rocks, and one which was followed mainly because it was, indeed, a new departure in experimental petrology. This narrowness of treatment, however, was destined to be rapidly transgressed, and one by one investigators became imbued with the broader potentialities of the subject, when it was realized to what extent fundamental problems in stratigraphical geology were capable of solution along these lines. Questions concerning the genesis of a sediment, involving not only ideas as to its source of origin, but also definite conceptions of its mode of transport and deposition, the nature of environmental and climatic conditions at the epoch of its formation—together with the pertinent aid which the subject affords to palæogeographical restoration—are all embraced by systematic petrographic examination of a series of deposits. It is not difficult, therefore, to appreciate the reasons underlying the rapid evolution, such as has taken place within the last twenty-five years or so, of a science offering so many far-reaching possibilities.

The foundations of the subject were undoubtedly laid by Sorby, whose work and publications (especially his two presidential addresses before the Geological Society in 1879 and 1880) are now classical. Later, in 1887, A. Dick recorded his observations on the Bagshot Sands of Hampstead, which included a description of the heavy mineral constituents; in this same year Teall also published certain methods bearing on the examination of sediments, while three years later W. M. Hutchings contributed an important paper on the subject.

In 1895 Retgers investigated the dune sands of Scheveningen, Holland; his work was certainly on modern lines and a distinct advance on that of his predecessors. W. Mackie next contributed to the advancement of the science by his researches on the Sands and Sandstones of Eastern Moray, published in 1896, and by a masterly consideration of the mechanical factors involved in the rounding of sand grains, published in 1897. The year 1900 saw the publication of T. G. Bonney's paper on the Bunter Pebble-Beds of the Midlands, in which he dealt with their petrography, mode of transport and their possible sources of origin, while the subsequent researches of H. H. Thomas, F.R.S., published in 1902 and again in 1909, marked a very definite advancement both in method and interpretation of results. More recently still, several British workers have contributed to our knowledge of sedimentary deposits, particularly Messrs. Boswell, Brammall, Crook, MacDonald Davies, Double, Fleet, Gilligan, Illing, Mackie, Rastall, Stamp and Wooldridge, whose combined teaching has done much to widen the scope and potentialities of the subject. [Bibliography, p. 487].

Attention is specially drawn to two papers of

outstanding merit which should be carefully read by all students of sedimentary petrography in its broadest applications; both are presidential addresses delivered before the Geological Society of London, one by Professor J. E. Marr, F.R.S., in 1905 on the "Classification of Sediments," the other by Professor W. W. Watts, F.R.S., in 1911 on "Geology as Geographical Evolution."

In the former paper an analogy was drawn between meteorograms, as recording meteorological variations, and "geograms," a word used by Professor Marr in place of the expression "Geological Column," and connoting, principally, variations in lithology and in organic assemblages that could be traced in a deposit, if a column obtainable from boring right through it were to be laid flat and studied from one end to the other. Although purely a hypothetical conception, the "geogram" is the ideal to which all petrographic investigations should tend, and even though the tracings are broken or discordant, as they are bound to be, the evidence will be none the less valuable and suggestive.

Professor Watts has enlarged this conception in the following words:—

"In order to obtain what Dr. Marr has called the 'geogram' of a formation in its greatest perfection, we require to know the entire extent of its variations, not only along its outcrop, but in that part which is hidden from sight; and we ought to be in a position to infer the probable variations in that almost equally important part which has been destroyed by denudation."

In a very suggestive article in the "Geological Magazine" for March and April, 1916, Professor Boswell discussed both the theoretical and practical tenets of the science, and their bearing on the pro-

gress of stratigraphical research. He has, in fact, given a very succinct account of the methods by which Professor Marr's "geogram" of a formation may be best attained, and the article is valuable for the co-ordination of facts and constructive criticism of hypotheses which it presents. Since then Professor Boswell has actively continued his researches on sediments, resulting in the presentation of a large store of inspiring data, while his periodic publication of "Progress of Investigation of the Mineralogical Composition of Sedimentary Rocks" (1923-1927), with its bibliographies and epitomes of relevant research, constitutes a co-ordinating link between British and Foreign work, of inestimable service to all concerned.

The period 1922 to the present time has witnessed a remarkable expansion in the study of sedimentary rocks and in problems of sedimentation, both at home and abroad, many geologists choosing the subject as fruitful ground for original enquiry and post-graduate research. Specific mention must be made of papers by A. Brammall and H. F. Harwood on the Dartmoor Granite, giving results of detailed geochemical and petrological investigations, profoundly affecting our conceptions of provenance and significance of sedimentary rock minerals, quite apart from the direct influence of this work in the domain of igneous petrology; also by S. W. Wooldridge on the London Basin and South-East England, in which the principles of the subject have found cogent application in working out the natural history of the region and the rocks concerned; also of the lucid analyses of cycles of sedimentation, rhythmic conditions, and the interpretation of stratal vagaries in France, Burmah and elsewhere by L. D. Stamp; equally of W. F. Fleet's

minutely detailed contributions to our knowledge of Palæozoic sediments of the Midlands, including his successful quantitative work on the heavy mineral suites involved.

In America the names of M. I. Goldman, E. M. Kindle, R. D. Reed, W. A. Tarr, F. G. Tickell, A. C. Trowbridge, W. H. Twenhofel and C. K. Wentworth, among others, are familiar as able exponents of and original contributors to sedimentary petrology in both academic and economic directions, and their writings have added much to the stratigraphical significance of the science. To W. H. Twenhofel and his colleagues on the Committee on Sedimentation, National Research Council (U.S.A.), we owe the succession of valuable reports on sedimentation considered from almost every possible standpoint, while the publication of the "Treatise on Sedimentation" (1926) certainly marked out a step in the right direction, that of co-ordinating promiscuously scattered data and clearing the ground for more definite advances in geochemical and geophysical knowledge of sediments of all kinds.

In Europe, excluding the British Isles, the names of J. Anten, I. Chelussi, E. Clerici, L. Collet, L. Deverin, A. Doyen, W. Wetzel, and especially Professors L. Cayeux, E. Haug, A. F. A. Lacroix and J. de Lapparent, are each implicative of unique and widely read contributions to the mineralogy, petrology and stratigraphy of sedimentary formations.

Every year sees an increase in the number of adherents to this branch of geology from all seats of learning throughout the continents of the world, and it is encouraging thus to recognize that sediments are at last generally receiving that detailed and widespread attention which is inherently their

due, but which has been somewhat sparingly given in the past by geologists as a whole.

There is, however, the danger that, notwithstanding the many and varied expositions of first principles, purely analytical phases of the subject may assume an undue prominence out of all proportion to their actual worth; it is useless amassing quantities of facts without seeking to reconcile them with hypotheses capable of explaining their significance, thus contributing to the development of the science; if theory lags behind practice, the result must inevitably be to retard rather than to advance the evolution of knowledge, no matter what branch of natural science is involved.

It is therefore necessary at the outset to stress the importance of the more fundamental aspects of sedimentary petrology, in particular the influence that its study must have on the progress of geological research. The fact that a large part of this book is concerned with descriptive mineralogy and petrology should in no way cloud the true perspective of the subject; the determination of the mineral constitution of sediments is but a means to an end, it is the first stage towards unravelling their history.

CHAPTER II.

SURFACE AND SUBSURFACE SAMPLES, STORAGE AND RECORDS.

Sampling (General)—Auger-Drill Samples — Bit-Samples — Bailer Samples (Cable-Tool System)—Core-Samples — Contamination—Fauck System Samples—Diamond Drill Cores—Containers—Labelling of Samples—Storage—Key-Samples—Sample-Indexing.

Sampling (General). Comprehensive sampling of a given sediment is at the outset a matter of great importance and one requiring systematic practice and care. Extensive deposits can only be satisfactorily sampled providing that there are numerous natural and artificial exposures accessible; this will obviously vary with the nature of the country in which investigations are being carried out.

Surface sampling, as distinct from subsurface sampling, should be effected at chosen intervals along and transverse to the strike of the beds, such intervals depending on the extent of the deposit, persistency of lithological facies, and topographical and structural considerations. Sampling in vertical sections exposed by quarries, cuttings, etc., involves collecting material from horizons determined primarily by change of lithologic facies and of texture of the rock. Where vertical sections are absent, samples collected superficially (unless the beds possess a marked regional dip) can only repre-

sent a very average composition of the horizon outcropping, and will in themselves be little criterion of the nature of the concealed beds; under such conditions "pitting" may be necessary for the production of samples within twenty feet of the surface, depending on local conditions, or failing that, a portable boring apparatus must be employed (see under *Auger-Drill Samples*, p. 12).

For sampling in depth (over 25 feet), the geologist has to rely entirely on material taken from borings (oil, water, etc.), and the efficacy of such sampling will depend largely upon the system of drilling employed. Abrasive methods normally yield core-samples, and these are the most valuable and easiest to deal with from the geological standpoint. Percussion methods (cable-tool system) are especially adapted to oilfield requirements, and sampling, by means of a bailer, can usually be carried out. The rotary system of drilling for oil (now widely adopted) unfortunately precludes all chance of obtaining uncontaminated samples from the "ditch," notwithstanding frequent assertions to the contrary, though the introduction of single and double core-barrels has done much to obviate this disadvantage (p. 15).

Samples of incoherent material, such as sand, can most conveniently be collected in the field in small numbered canvas bags, each capable of holding about 200 grms. of material. Care should be taken to record the precise locality and horizon from which the sample is taken. In collecting from a given exposure as, for instance, from a bed of sand three feet in thickness, and in order to obtain as representative a sample as possible from this bed, the bag should be held against the face and at the bottom of the bed, and a geological hammer used to remove material by drawing it from the top of the

bed downwards, the dislodged sand thus falling into the bag. Where there are several feet of rock exposed, this method can be repeated from one horizon to another, providing that the whole section is accessible.

Surface sampling involves in each instance the taking of small amounts of material from proximate points to make up one sample which shall be representative of the particular locality chosen, providing that some degree of homogeneity of deposit be in evidence; rapid lateral variation will necessarily narrow down the limits within which this form of sampling may be safely employed.

Plastic rocks, such as clays, obviously do not lend themselves to the foregoing methods of sampling, the material usually having to be cut out with a knife. It should be borne in mind that much larger samples of clay are required for proportionate yield of heavy minerals than in the case of sand; also that *the coarser the sand, the larger the sample necessary*, if a reasonable yield of mineral residue be sought.

Consolidated sediments, *e.g.*, sandstone, shale, limestone, as is the case with igneous and metamorphic rocks, must be hammered out in the usual way, the material being subsequently crushed if the accessory detrital minerals are required.

Take care always to obtain unweathered samples.

Auger-Drill Samples. During the course of geological field-work, where information concerning the solid rock beneath sub-soil or alluvium is sought in critical places, some device for procuring rapidly the desired samples has long been in request. In the early days of Wealden geology, the officers of the Geological Survey used to arm them-

selves with an instrument akin to a "cheese-taster" (as it was called), with which subsurface evidence was often quite satisfactorily obtained. From time to time various hand-drilling instruments have been used for a similar purpose, as for example, those described by A. C. Veatch in connexion with hydrological surveys in Louisiana.¹ It remained for Professor V. C. Illing to introduce and develop the use of the modern auger-drill in Trinidad, and the simplicity and efficiency of this instrument—simply a carpenter's auger attached to a suitable length of gas-pipe provided with a T-piece and rod for turning—has made it a most popular method of obtaining shallow subsurface samples of soft rocks such as clay, sand, silt, marl, etc. Its use is not practicable with hard rocks or with coarse, loosely consolidated materials such as flint-gravel. Holes up to 20 ft. or more are possible by hand-turning alone, depending on the nature of the rocks traversed; the use of a tripod and winch with suitable pulley to aid in hoisting the pipe out of the hole, enable far deeper borings to be made successfully.

The samples obtained by the auger-drill are those which are held in place in the convolutions of the bit; especially if the sediment is a little moist it will readily adhere; if drilling through dry, loose sand, a slight water-flush will supply the necessary amount of "bind." The sample clinging to the bit should, while still attached, be pared of its outer surface with a knife or suitable scraper, as the superficial material is liable to contamination from the sides of the hole as the bit is withdrawn; it is then recovered in the form of a "spiral" by running the finger from the cutting

¹ A. C. Veatch, "Water Resources in N. Louisiana," etc., *U.S.G.S., Prof. Paper*, No. 46, 1906, ch. 3, p. 93.

point of the bit upwards round the grooves, or alternatively, holding the bottom end of the bit between thumb and finger of the left hand and turning the bit itself in a clockwise direction with the right hand. Exceptionally clean samples can be obtained in this way, which are invaluable, not only for petrographic purposes, but for checking concealed rocks during the course of field-mapping.

Samples thus obtained may be segregated in canvas bags (as above) and thus suitably transported, or, better still, an oilfield sample-container (p. 18) can be employed.

Bit-Samples. So-called "bit-samples" or "drill-cuttings," *i.e.*, rock-fragments clinging to the bit of a rotary- or cable-tool and thus recovered, must generally be regarded with suspicion, not only of possible contamination, but often of precise position whence derived; in the absence of other means for taking samples, however, such "cuttings" must often suffice; they are certainly better than nothing at all. Bit-samples obtained from a rotary-bit are invariably contaminated with mud; those obtained from a cable-tool bit are perhaps more reliable since they are less prone to that particular influence. With samples of this description, a great deal depends upon the type of bit employed, the efficiency of the driller and the care with which the cuttings are selected, preferably by the geologist.

Bailer Samples (Cable-Tool System). These "cuttings" are frequently all that is available as a record of the rocks penetrated, and in the absence of caving strata or drilling mud, are generally uncontaminated and reliable. The cable-tool system being usually employed for hard rocks, especially limestone, results in the bailer yielding fragmental

samples, normally, however, of sufficient size for subsequent production of thin sections.

To a large extent the disadvantages of bailer "cuttings" are overcome to-day by using cable-tool core-barrels, which lead to the successful recovery of good cores with practically all types of rock; such core-samples are dealt with in the same way as other cores obtained from rotary drilling systems.

Core-Samples. The notable advance made during the last few years in the technique of sub-surface stratigraphical correlation, whether dependent on heavy minerals, micro-organisms, or both, is due largely to the increased facilities offered by modern drilling equipment for obtaining core-samples of the rocks traversed. The introduction of the single or double core-barrel, especially in the American oilfields, and the more extended use of diamond drills, have both been instrumental to this end. Hitherto, pure samples have been difficult to realize with most drilling systems in vogue, especially the rotary, and quite an appreciable amount of the trouble encountered in microscopical investigations has been traceable to interfering material from mud-flush, particularly if heavy mineral mud (*e.g.*, barite, hæmatite) be employed for any reason.

It is desirable at the outset to emphasize the fact that the use of the core-barrel does not entirely overcome the problem of contamination, as will be shown later; also, a continuous core of a given hole, while it may be theoretically desirable from a geological standpoint, is not always practicable; mention is made of this point advisedly, in view of the tendency in some quarters to exaggerate the claims of the core-barrel for petrographic work. In practice, cores are generally taken

at regular intervals where little or nothing is known of the subsurface rocks; such intervals may be every 30 feet, 20 feet, 10 feet, or less in exceptional circumstances; where more is known of the rocks being drilled, the intervals may be much greater until critical horizons are reached, such as oil-sands, cap-rocks, etc., when close coring becomes a matter of necessity.

That the use of the core-barrel does not eliminate the contamination factor is due to the fact that drilling mud is liable to "pack in" with the rock, especially if the latter is soft or when drilling pressure is high. Many of the core-samples examined by the author have obviously suffered contamination in this way, in some cases the heavy mineral assemblage varying from different parts of the same core! A. C. Rubel¹ has discussed some pertinent aspects of this question of contamination, and has shown how in some cases the drilling mud may not only coat the outside of the true rock-core (which frequently happens), but may be forced to penetrate a loose sand for example, giving rise on compaction to a core of alternate sand and mud, instead of a core of definite sand, with resulting inaccuracy in "logging" the well, to say nothing of the ultimate petrographic examination. Another case in the author's experience is where the drilling mud itself gets cored, *e.g.*, when drilling through fine mobile sand which, masked by the flush, results in the erroneous record of "mud," "shale," "gumbo," etc.

To guard against misleading appearances and possibilities of this nature, the following precaut-

¹ A. C. Rubel, "Determination of Core-Samples in Core Drilling," 9th Ann. Rep., Calif. State Mining Bureau, vol. ix., 1924, No. 11, pp. 5-11.

ions should always be taken before submitting cores to treatment for petrographic analysis:—(a) with soft rocks always scrape off the outer margin of the core; with a $2\frac{1}{2}$ inch core, for example, this implies discarding at least $\frac{1}{4}$ in. to $\frac{1}{2}$ in. of outside material; (b) take the interior of the sample for investigation wherever possible; (c) at frequent vertical intervals, as represented by the cores, split a sample longitudinally to ascertain whether any extraneous material (drilling mud) has penetrated the rock; if this has happened it will usually be indicated by the interdigitation of the mud and the rock, the mud-laminæ being continuous with the mud forming the outside coating to the core; (d) if a mud-flush is used in which the mud is obtained from the same supply throughout the drilling of the well, take a sample of the material (silt or clay) employed from time to time, and examine carefully as a check on possible impurities. Often the mud employed is furnished by the finer shale- or clay-cuttings obtained during the early drilling of the well, so that, unless care is taken, critical constituents of a higher horizon may quite easily find their way into deeper cores, and thus be misinterpreted in subsequent examination. It is apparent, however, that the possibility of contamination is greater the softer the rock; on the other hand, with hard rocks the percussion drilling system is resorted to, and where the hole is being drilled dry, or nearly so, or where a cable-tool core-barrel is employed, the contamination factor may be expected to prove far less serious.

Fauck System Samples. What is known as Fauck's patent "Express" drill produces in normal circumstances good cores from all kinds of rock, but chiefly those which ordinarily are drilled with the standard cable-tools. The system is in

principle a water-flush one, but it is also adapted to dry drilling, and in either case the samples obtained are quite reliable and tend to be uncontaminated.

Diamond Drill Cores. Where a diamond drill is used, the core-samples are probably less contaminated than those obtained by any other means; in fact, exceptionally with very loose sediment, this system of drilling provides the geologist with some of the very best material for ultimate microscopical examination. "The value of the solid core secured by the diamond drill cannot be over-estimated. These cores show in exact sequence the various rock-layers pierced, and record accurately the depth, thickness and character of each one, and its dip and strike. As compared with ordinary drilling methods, which merely furnish cuttings brought up by the return water, the diamond drill core represents definite, complete knowledge, the other, guess work."¹ Quite apart from the investigation of micro-organic or heavy mineral constituents extracted from such cores by crushing, this form of well-sample lends itself more readily than any other to analysis by means of thin sections.

Core-sample "splitters" and extractors are supplied as part of the standard coring equipment for all drilling systems.

Oilfield Sample-Container. For hard or repeated use, the ordinary canvas bags or unprotected tins are of little good as sample-containers, and in oilfield practice it is customary to employ a strong pattern wooden container for transporting samples from drilling wells to the laboratory, also to ensure as far as possible no mixing of materials

¹ "Diamond Drilling for Oil," Sullivan Machinery Co., Chicago, 1923, p. 9.

either on the derrick-floor or subsequently during conveyance. This type of container is so consistently successful, that it may with advantage be used in other circumstances where systematic sampling is contemplated.

The pattern recommended by the author consists of a flat, shallow wooden box, with lid, constructed externally of 5-8" or $\frac{3}{4}$ " white wood (teak for the tropics) and of such dimensions that it may be subdivided inside by 3-8" partitions into twelve cells, each cell being capable of accommodating either a rectangular tin 3" x 3" x 4" or a round cigarette tin (50 size); both forms of tin should have lids. The container is fitted with substantial hinges and fasteners, and a handle, usually of leather, is attached to the front similar in position to the handle of an *attaché* case.

For core-samples, special open rectangular wooden trays, longitudinally partitioned, are generally employed. These depend for dimensions on the diameter of the cores taken. In the case of $1\frac{1}{2}$ " cores, for example, the convenient tray is one which accommodates in six divisions 20 ft. of core, i.e., 3' 4" per division. More core per tray, especially if the diameter is larger, results in very heavy, unwieldy containers, though where labour is not difficult this may be no drawback. Such core-trays are used both on the wells and for permanent storage.

Labelling of Samples. When dealing with a large number of samples, the possibility of confusion has naturally to be guarded against. Much trouble of this kind can be avoided by careful and systematic labelling. All samples, whether cores or loose material in sample-boxes, bags or other containers, should be clearly numbered as soon as they are collected, serial numbers in con-

junction with an index-letter denoting a given area or locality being preferable; thus differentiation from previously collected material is automatically made. In oilfield practice the field or lease (often signified by a letter of the alphabet or suitable field-sign), the well number and depth, are desirable, *e.g.*, " ' B.B.' 27—1875 ": *i.e.*, " B.B." lease or field, well No. 27, depth 1,875 feet; the next sample might bear the label " ' B.B.' 27—1890," and so on. When in the laboratory a given series of samples from the same well are in process of investigation, the depth numbers obviously suffice for reference.

Permanent Storage. Methods of storing samples vary largely according to taste, custom, facilities, climatic conditions, and the nature of the materials. With loose sediments or " cuttings " glass bottles with wide necks and corks or flat-topped stoppers to fit are employed where large quantities of material are required. For small quantities, storage is effected either by cardboard containers (cylindrical with screw tops), strong canvas-lined envelopes or glass specimen-tubes; the author favours the latter receptacles, especially those with screw metal tops, size 3" x $\frac{3}{4}$ ", 4" x 1", 5" x 1" or 6" x 1"; where cheapness is a desideratum, 4" x 1" tubes with flat corks are quite good. Cardboard or canvas containers are apt to be destroyed by insects or mice, especially in hot countries, or they may suffer quickly from damp. Glass has the disadvantage of being liable to breakage, especially in transport; tins resist attacks of insects and, to some extent, damp, but they quickly rust if not kept in dry surroundings.

Always put a label inside the sample-container as well as on the outside.

With core-trays, it is usual to paint or other-

wise mark on both ends of the container the field-sign, well number and limiting depths represented by the cores inside; the boxes are then stored side by side on suitable shelves in such a way that the "end-labels" can be rapidly read, and any given series of cores referred to easily. The cores from one well are always kept together.

Key-Samples. The advantage of setting aside small portions of important samples for future reference and comparison with material subsequently obtained, is sufficiently obvious to require no further emphasis. Such "key-samples" may be representative of particular stratigraphical subdivisions, zones, horizons, oil-sands, prolific foraminiferal clays, etc., etc., and are independent of any microscope slides of mineral residues or organisms ultimately prepared.

Of a similar significance are the specific outcrop specimens collected for purposes of comparison (on analysis) with equivalent rocks likely to be met with in well-samples; see p. 49.

Sample-Indexing. The storage space necessary for the accommodation of many rock-samples is liable to grow considerably in excess of laboratory facilities for this purpose; hence some system of indexing or filing information concerning samples soon becomes essential, and, in point of fact, is much favoured in "subsurface" laboratories concerned with work of this kind. The samples can be stored outside in a suitable storehouse, shed or similar place, while the card-index is a requisite part of the laboratory equipment. Generally a card is devoted to each sample (in the case of oil-well samples), and contains information regarding field or lease, position, name and/or number of well, depth, geological horizons proved and other relevant data. In some cases a separate

FIELD	X. Y. Z. Co.		SAMPLE No.	DEPTH ¹ 2190'-2195
WELL No. . . .				CASE No.,
FORMATION	HORIZON			DRAWER No.
SAMPLE ²	BY WHOM TAKEN		DATE	
DRILLER'S LOG ³		COLOUR (W or D) ⁴		
MEGASCOPIC DATA				
REMARKS ⁵				
VISIBLE ORGANISMS				
TEXTURE	GRADE	SHAPE	ACCESSORY MINERALS	
MICRO. ANAL. ⁶	THIN SECTION No.		% TOTAL SAMPLE	
			AVERAGE GRADE	
			AVERAGE SHAPE	
			SPECIAL FEATURES ⁷	
(SEE OVER FOR DETAILS) ⁸				

Fig. 1. Specimen Well-Sample Card as designed and used by the author. Actual size 8" × 5".

NOTES:—1—Depth-range is inserted boldly in top right-hand corner to facilitate reference when in file. 2—State here whether core, cuttings, etc. 3—Description as entered in driller's log. 4—W = wet, D = dry. 5—Insert here any special observations, e.g., oil, asphalt, water-sand, etc. 6—Microscopical analysis. 7—Note here any peculiar index-minerals or characteristics of the suite. 8—Reverse side of card used for list of minerals or special data.

card-index is made for recording petrographical and/or palæontological data obtained from certain samples, for the purpose of rapid reference when carrying out microscopical examination of new material, and to save time in searching a number of different and possibly irrelevant slides; or such information may be logged on the one card.

Index-cards and files vary according to requirements; a useful size is 8" x 5", which provides enough room (both sides) for all possible information. A suitable standard type for well-samples is reproduced in *fig. 1*.

To obtain the fullest use from a card-index system of this character, it should be used in conjunction with graphic well-logs of each well drilled. Incidentally, special samples, water analyses, oil and gas horizons, etc., etc., can be logged on different coloured cards placed in proper sequence with the sample-cards.

CHAPTER III.

LABORATORY TECHNIQUE.

Dry Samples—Megascopic Examination—Thin Section Preparation—Schedule of Equipment—Points in Mounting Friable and Impregnated Rocks—Conventional Thickness of Rock-Sections—Treatment of Incoherent (Detrital) Materials for Heavy Minerals, Micro-Organisms, etc. — Schedule of Equipment—Single Separations—Bromoform and Bromoform-Benzol Solutions — Mounting of Sand Grains for Microscopical Examination—Systematic Procedure for Simultaneous Investigation of Samples for Micro-Organisms and Heavy Minerals—Special Methods of Concentration—Panning—Sieving—Elutriation—Magnetic Separation—Electrostatic Separation—Dielectric Separation—Vibration Methods—Use of Other Heavy Liquids and Fused Salts—Detrital Mineral Concentration by Hand—Elimination of Prolific Minerals from Heavy Residues—Treatment of Argillaceous, Calcareous, Carbonaceous and Impregnated and Crushed Rocks—Refractive Index (Immersion) Methods.

Dry Samples. Sedimentary rock-samples should be thoroughly dried before examination. Oil-well samples are generally wet and in this state are apt to prove misleading in diagnosis, particularly if any oil is present. Where a number of samples is being constantly handled, the most convenient and satisfactory means of drying them is on a long rectangular iron plate, about $\frac{1}{4}$ " thick, suitably supported on tripod-stands and heated by bunsen gas-burners, or, in the absence of gas supply, by ordinary oil-stoves; in the latter case

the iron plate may be supported on trestles with pieces of asbestos inserted between the wood and the iron. The samples are emptied from their containers, spread out on square-cut pieces of paper placed on the plate, and thus left to dry.

Megascopic (Macroscopic) Examination. Prior to special treatment for detailed analysis, the maximum information should be obtained from samples by eye-inspection, aided with a hand-lens and also with a binocular microscope (p. 83), such information being recorded at the outset on the appropriate index-card (p. 22) or in a sample record-book. The following are the chief points of observation:—

- a. Identification.
- b. Colour.
- c. Texture.
- d. Composition (inorganic constituents).
- e. Fossils or organic structures.
- f. Bedding, lamination, cleavage, etc.
- g. Special structures or characteristics.

a. Specific identity may not always be possible without recourse to thin sections or special tests (pp. 49, 51). The chief difficulties arise with compact, fine-grained rocks, *e.g.*, limestone, marl, salt, anhydrite, gypsum, while different coloured shale or mudstone fragments may simulate other types. Knowledge of what to expect from any particular horizon may help, but doubtful cases should always be subject to exhaustive investigation before "labels" are applied with confidence.

b. Colour varies markedly in sediments according to whether the samples are wet or dry. Frequently the former state aids diagnosis, but inherent colour must be determined in the dry rock. There are standard colour-systems in use by some

petrologists, *e.g.*, Munsell, Ridgway,¹ and N.R.C.C.S.² schemes, which are useful for comparative purposes. Note should be taken as to whether the colour is due to particular ingredients, whether superficial stain or tarnish, a weathering product, or inherent to the rock as a whole.

c. The coarse, medium, or fine texture of a rock should express relationship to its actual mechanical analysis, but short of quantitative data, the terms are purely comparative. Experience of varied sedimentary rock-types and an "eye" for grade-size of components, however, enables the observer to use these terms more or less accurately. Texture should apply as an average to the specimen as a whole, but may, of course, be restricted to cementing material independently of the large constituents, *e.g.*, conglomerate with $\frac{1}{2}$ " pebbles set in a *fine* compact matrix. The art of "textural analysis," as it is called, is of recent introduction; as a quantitative estimation, its consideration is deferred to subsequent paragraphs (p. 115). Qualitatively, clay, marl, siltstone (components <0.1 mm.) imply fineness of texture, individual particles being practically invisible to the unaided eye in the case of siltstone, entirely so in the argillaceous types. Normal sandstones, grits and the like, frequently approximate the size-limits 0.25 mm.-0.5 mm., and are thus correctly labelled "of medium texture." Above the larger dimension, the particles assume characters which tend to guide the observer to the correct definition "coarse," especially 1 mm. and 2 mm. particles, while the presence of pebbles automatically leads to this

¹ R. Ridgway, "*Colour Standards and Colour Nomenclature*," 1912.

² National Research Council, Committee on Sedimentation (U.S.A.). Colour-Chart obtainable from headquarters, Washington (D.C.).

description unless the matrix alone is considered (*supra*). Limestones void of visible organic remains are usually of the compact, fine textured type; so-called "shelly" limestones approximate the coarser rocks; oolitic types vary from medium to coarse texture, pisolitic varieties invariably coming under the latter category. *Shape does not affect the question of texture.* Texture has some bearing on "tightness" or "openness" of rocks acting as oil-containers, though it must be remembered that it is not alone an indication of porosity or permeability.

d. The composition (inorganic constituents) is essentially a record of the lithology of the sediment, and implies recognition of those features characteristic of particular rock-types, *e.g.*, sandstone, grit, arkose, quartzite, shale, marl, limestone, etc. Naturally it also implies the mineralogy of the sediment in so far as this is determinable without microscopic aid. In the coarser rocks the shape of the prominent constituents, angular, subangular or rounded, comes into consideration, especially where pebbles are concerned (p. 113), but in the majority of cases "shape" of particles is more accurately recorded under the microscope (p. 85). Other points to note under this heading are surface characters dependent on weathering (if any), the uniformity or heterogeneity of the components, and any unusual lithologic features.

e. Fossils or organic structures, whether determinable or not, should be recorded as such when occurring in the rock. Obviously, if determinable, the rock becomes distinctive at once; if not, even the presence of organic remains, either vegetable or animal, is of some diagnostic value. There is seldom difficulty in recognizing constituents as

organic remains, even if they are not sufficiently well preserved to afford clues to their precise nature and origin; a hand-lens is always effective in this connexion. Some distinction should be made between dominantly fossiliferous rocks, those which are only partially fossiliferous and those whose organic remains are few and far between. The orientation of the organisms should also be noted. The nature of the petrification is important; it may be calcareous, siliceous, pyritous, phosphatic, limonitic, rarely other minerals. The calcareous forms include calcite and aragonite preservation; in the former category fall most of the vitreous forms of *foraminifera*, many sponges, corals, echinoderms, polyzoans, brachiopods, etc.; lamellibranchs consist mainly of aragonite (except the common *Ostrea* and *Pecten*), as also do gastropods (excluding some species of *Fusinus*) porcelainous forms of *foraminifera*, and cephalopods (ammonites frequently show much secondary calcite and pyrite); in crustaceans the shell usually consists of chitinous material, calcite and phosphate of lime.¹ Where only casts or impressions of the organisms are seen, the nature of these should be carefully ascertained and, if desired, wax or plaster moulds taken. Note the significance of the presence of glauconite in association with organic remains (p. 443).

f. Distinction should at once be drawn between specimens exhibiting bedding or lamination, cleavage, or any linear or curvilinear structures, and those devoid of same. Note whether the bedding, if developed, is uniform or variable, thin or thick, regular or cross (current-bedding); whether shaly-lamination is apparent or not; whether the bedding-surface is smooth, flat,

¹ H. Woods, "*Palæontology*," 1909, pp. 4-8.

crumpled or rippled and, if the latter, the nature of the marking (symmetrical or asymmetrical); cleavage, though it may be clearly apparent to megascopic observation, is better studied in thin section, especially in its relationship to reconstituted minerals, etc.

g. Special structures or characteristics are those which tend to give individuality to any particular rock-type, such as surface-markings, mud-cracks, rain-prints, worm-tubes, -tracks, -impressions, mineral "spots," peculiar modes of weathering, minute warping and shear-structures, angular jointing (with bedding or cleavage), secondary mineral developments as veins, blebs, cavities, bituminous impregnations, distinctive constituents, etc., etc.: in short, any feature which, by its conspicuous and possibly widespread development, tends to individualize the rock and thus render its identification and history easy of interpretation.

Thin Section Preparation.¹ The methods of thin section preparation are now so generally known as to require only brief treatment here. It may be observed, however, that in general sedimentary rocks demand a greater degree of skill in the manufacture of really thin slices, owing to their inherently softer and more friable character, than do igneous rocks; in fact, many sedimentary rocks demand special treatment and technique before sections can be made from them at all; such departures from normal routine are discussed in the sequel (p. 35).

It must also be born in mind that field-laboratories are not usually equipped with elaborate rock-cutting machines, and that hammered fragments from outcrop specimens or, as is more common,

¹ For fuller data see H. B. Milner & G. M. Part, "*Method in Practical Petrology*," Cambridge, 1916.

well-sample chips or core-flakes, constitute the only available raw materials. It requires considerable experience and skill, for instance, to take a bailer cutting of, say, $3/8''$ diameter (perhaps the largest piece available of a critical rock-horizon penetrated) and produce therefrom a satisfactory slice which will respond to the most refined optical examination; however, it can be, and often is done with remarkable consistency by lapidaries who really know their work.

While it is freely admitted that individual taste and experience play a large part in the selection of appropriate apparatus for this work, the author has found from long experience that the following equipment is most economical and satisfactory for all field-laboratory purposes, or for those operations where neither personnel, time nor money is available for large-scale procedure and output:—

Steel Plate (machined) for coarse grinding, circular, $12''$ x $1''$ or $12''$ x $3/4''$; alternatively square, $12''$ x $12''$ x $3/4''$.

Glass Plates with ground edges, square, $12''$ x $12''$ x $3/8''$ for medium and fine grindings.

Wooden Trays (3), preferably teak (essential wood for tropics) to accommodate above plates, $13\frac{1}{2}''$ x $13\frac{1}{2}''$ x $1''$ deep (inside dimensions).

*Copper Plate about $15''$ x $4\frac{1}{2}''$ x $3/16''$ for heating balsam on glass slips, to accommodate 12 at a time.

*Tripod Stands (2) to hold copper plate, $8''$ or $10''$ high depending on burner used.

*Microscope Slips, white glass, ground edges, $3''$ x $1''$, 0.75 mm.-1 mm. thick (supplied by the gross).

*Cover Glasses, No. 1 quality, rectangular, $1''$ x $7/8''$. (Approximately 1 oz. per gross of slides.)

*Forceps, polished steel or nickel plated, with ribs and fine points, 10 cms. long.

*Soft Tooth-Brush for removing surplus balsam in methylated spirits.

*Photographic Developing Dish ($\frac{1}{2}$ -plate size) or large Evaporating Basin for cleaning slides.

*Canada Balsam (*filtered*, not solution in Xylol) in 1 lb. bottles (coloured glass).

Carborundum: grit 90 for coarse grinding, grit 220 for medium grinding, minute powder 60 mm. for fine grinding.

Emery Powder FFFF for fine grinding and special work.

Putty or Rouge Powder for polishing rock-surfaces.

Shellac Flakes for "cooking" friable or soft rocks (mix 2 parts of balsam and 1 part shellac).

Bakelite Cement for friable rocks.

*Methylated Spirits, Benzol or Xylol for removing surplus balsam (the first recommended for preference).

Glycerine for special "dry" grinding.

*N.B.—These materials are also used in the mounting of incoherent sediments, heavy mineral residues and the like. When indenting for the above equipment, quantities should be ordered which are commensurate with the work in view and with the facilities available for replenishment of supplies as materials become exhausted.

If some form of rock-cutting machine is employed, add to the above list the following:—

Spare cutting discs.

Extra supply of coarse carborundum.

Diamond Dust ("Diamond Splint").

Flint Pebbles for bedding diamond dust in cutting-disc edge.

Thin lubricating oil or paraffin.

The following procedure applies to normal hard rocks, whether igneous, sedimentary or metamorphic:—The fragment is first ground down with coarse carborundum mixed with water on the steel plate until as large an area as possible, of uniform surface, is obtained. It is then washed free of carborundum and transferred to the medium (glass) plate, where a similar grinding with medium carborundum reduces the surface still further, removing all scratches, etc., due to the

coarse grinding, and preparing the flake for the next grinding on the fine plate, using "minute powder" or emery as detailed above. The utmost care should be taken to see that no coarse carborundum finds its way on to the medium plate, and that no medium powder has access to the fine plate, otherwise the plates will soon be ruined, if not the slices under preparation; this possibility is easily avoided by careful washing under running water between each grinding, and by keeping each of the trays some distance apart. After a satisfactory surface has resulted from the fine grinding (it should show no scratches or blemishes of any kind), the chip is well washed, then dried on a hot plate.

It is often found that with many sedimentary rocks the coarse abrasive is too drastic, and a cautious use of the medium grit is all that is necessary to secure both rapid and successful results. In soft rocks it may only be practicable to grind steadily with minute powder or emery, whichever is preferred, if a reasonable size fragment is to be saved from disintegration. Much of this trouble can, however, be obviated by preliminary cooking of brittle or perforated rocks in the shellac-balsam mixture (above) for half-an-hour previous to grinding; use a tin-lid on the hot plate for this purpose. In special cases dry grinding may have to be resorted to: see p. 36.

Once the rock-chip is dried after the first grindings, the next operation is that of mounting it on the glass slip, and on this process the ultimate success of the work depends. "Some balsam is spread on the glass slide and heated on the copper plate. It is sufficiently cooked when a thread drawn out between the points of a pair of forceps becomes brittle when cold. *Insufficiently cooked*

balsam will absorb carborundum during the second grinding. Overcooked balsam is too brittle and will break away, thus exposing the edges of the rock-chip which it is there to protect. When the balsam is just right for mounting, the rock-chip, which has also been heating meanwhile, is placed, polished surface downwards, on the slip, and firmly pressed down, care being taken to exclude air-bubbles. If any of these remain, the slip must be reheated and the chip worked about until the bubbles are pressed out. When cold, the second grinding may be proceeded with."¹

When thoroughly cold and firm, the chip is ground down once again on the coarse plate, if it initially stood this abrasive, until it is about 1 mm. thick, the glass slip being used as a convenient holder. The surface attained, it is washed and transferred to the medium plate where further grinding with the 220 grit reduces the chip to a state of translucency. It is washed again and finished on the fine plate. If during the final grindings balsam tends to come away from the rock, either transfer the latter to a new slip on which a fresh supply of balsam has been cooked in readiness, or pour suitably cooked balsam on to the specimen so as to surround the exposed edges completely, and allow to harden.

In the final stages of grinding on the fine plate, great care must be taken to avoid unequal pressure on different parts of the slice; if there is a tendency to thickness in any particular area of the slice, it may be checked by grinding that part on the edge of the plate until uniformity of surface is obtained. Check carefully and often the progress of operations with the microscope, using crossed nicols to ascertain thickness (p. 36).

¹ Milner and Part, *op. cit.* p. 9.

When the slice is of requisite thinness, dry on the hot plate until all moisture is driven off. In the case of normal hard rocks, fresh balsam may be placed on the dried chip, slowly cooked to the right degree, and then covered with the cover-glass on which a thin coating of balsam has also been allowed to cook. With soft rocks it is advisable to cook the fresh balsam on a separate slip and then to pour it on to the dried slice, following this operation at once by placing the cover-glass in position as in the first case. Air-bubbles are expelled by gentle pressure with the forceps on the cover-glass while the balsam is in a fluid state.

With the cover-glass in position and the air-bubbles expelled, the slide is allowed to cool, and then all surplus balsam adhering to the edges of the slip is cleaned off with the tooth-brush in methylated spirits. The cleaning process may be accelerated in skilful hands by flaking the solid balsam with a sharp knife, then cleaning with xylol, but care must be taken to see that the cover-glass is not damaged in the process; also that the xylol does not eat away the balsam from beneath the cover-glass. When clean, polish the slide with wash-leather and label with $7/8$ " square labels at each end. In this connexion it should be remembered that gummed labels may perish or become detached in the tropics; in such cases grind each end of the slide on the coarse plate until opaque, if this is not already achieved, and write the description of the slide with Indian ink on the surface thus produced. Alternatively, an identity mark or number can be scratched on the slide with a diamond, or etched with hydro-fluoric acid on a wax-covered area, the wax being suitably incised with a fine wire point; this last, however, is a tedious and not very satisfactory procedure.

POINTS IN THE PREPARATION AND MOUNTING OF FRIABLE AND IMPREGNATED ROCKS FOR THIN SECTION EXAMINATION. Those who have had experience of producing thin sections of friable rocks or impregnated sediments, are aware of some of the difficulties occasioned by these types; the tendency of the former to crumble or disintegrate, if not in the early stages of grinding, often just before the section is achieved, and the trouble caused by fluxing of the bitumen when mounting with warm Canada balsam in the case of the latter, are familiar troubles to be overcome. In these connexions, E. J. Tallin, of the Geological Department, Imperial College of Science and Technology (to whose skilful preparations of such rocks as thin sections the author has on many occasions been indebted in the past) has kindly contributed the following brief account of his own technique:—

“ Before proceeding with the usual grinding of such rocks as clays, shales, some limestones, certain loosely cemented sandstones, lignitic material, schist and any weathered or much altered rock, the slice to be sectioned should be thoroughly warmed to get rid of any moisture present. It should then be immersed in a bath of Canada balsam and cooked until this medium is tough but not brittle, just hard enough, in fact, to be impressionable with the finger-nail. When quite cool, the grinding of the slice may be proceeded with in the usual way.

“ The above method is not applicable to bituminous rocks since in these cases slight warming causes the bitumen to migrate, either leaking out altogether, saturating parts of the rock not previously saturated, or fluxing with the Canada balsam. The effect of such movement is likely to give an erroneous impression of the impregnation when the section is examined under the microscope. Also, many of these rocks on warming become warped, even corrugated, thus preventing the achievement of a uniformly thin section. Again, certain constituents of oil-bearing rocks are soluble in water, hence these are lost if the ordinary methods of preparation are adopted.

“ Dry cutting such rocks is therefore advisable, the cutting disc being lubricated with a little glycerine. The slice thus obtained is carefully ground on a metal plate with 3F carborundum, then with washed flour emery, and lastly on a Water of Ayr Stone, using glycerine as before. Canada balsam used for mounting the slice is previously cooked before it is poured on to the glass slip, and the slice must be quite dry before it is mounted. The second grinding is carried out on a carborundum cloth (grit 90) fastened down to a flat surface, and is proceeded with until the slice is flush with the surface of the balsam. The back of the glass slip should be periodically examined for ‘flaking,’ *i.e.*, fracture of contact between the slice and the slip. Final grinding is carried out on fine carborundum cloth; in some cases this is too drastic, when gentle rubbing on a selvyt cloth may be tried; this procedure is, however, very slow. When the slice is of the requisite thinness, it is dried and covered with a cover-glass on which sufficient balsam has previously been cooked; this avoids warming the section more than necessary, and in this way the slide is completed.

“ With very soft or plastic rocks, the use of a razor blade or even a microtome may prove more satisfactory than trying to grind down sections in the usual way.”

Bakelite cement has been much employed of late with considerable success for all kinds of soft and friable rocks, also for coal sections, cements and similar materials. Its application to thin section work has been described by C. S. Ross.¹

Conventional Thickness of Rock-Sections.

In quartz-bearing rocks, this mineral is used as the index of thickness, which should be of the order of 25 microns (about one thousandth of an inch), and should be revealed by the white, grey and pale yellow birefringence (1st order) colours between crossed nicols. In the absence of quartz, felspar may be taken as an indicator. In calcareous rocks, the section is taken as thin as possible, *i.e.*, until the calcite is quite transparent in ordinary

¹ C. S. Ross, *Amer. Journ. Sci.*, ser. 5, vii., art. xxxvi., p. 483.

light or shows characteristic pinks and greens under crossed nicols. For a practical method of utilising birefringence as a diagnostic factor, see page 88.

Treatment of Incoherent Materials for Recovery of Heavy Minerals, Micro-Organisms, etc.

Although the principles are much the same in each case, the methods now to be described differ according to whether single separations of heavy minerals or micro-organisms are required from individual samples, or whether a large batch of samples (*e.g.*, well-samples) is to be treated simultaneously for both forms of concentration. Methods for single separations are first discussed. Both panning and sieving may be necessary before proceeding with separations: see pages 55-56.

At the outset, a schedule of essential equipment for this particular work may be conveniently given here:—

Iron Pestle and Mortar for crushing rocks, $8\frac{1}{2}$ " diameter, bell-shaped, turned.

Sieves for ordinary use, in japanned tin frames, with cover and bottom, 6" diameter, 30-, 60-, 90- mesh.

Sieves for special quantitative work, I.M.M. pattern, brass weaving in suitable frames, 8" diameter, with cover and bottom, 30-, 60-, 90-, 120-, 200- mesh. (N.B.—These sieves can also be obtained of 5-, 8-, 10-, 12-, 40-, 50-, 70-, 80-, 100-, 150-, and 200-mesh, but as they are expensive, a choice should be made which is suited to the work in view; the five quoted above are those in most common use).

Sieves for coarse materials, zinc circular hole (metric), with cover and bottom, 16 cms. diameter, with holes $\frac{1}{2}$, 1, 2, 4 and 7 mm. in diameter.

Evaporating dishes, 16 cms. wide, shallow, porcelain, for cleaning sediments.

Glass stirrers made from 5 mm. glass rod supplied in metre lengths by the 1 lb. weight.

Wire Gauze, iron, with asbestos combined, cut in 5" x 5" squares for heating basins.

Tripod Stands, 8" or 10" high according to size of burners used.

Sand-Bath for drying acid-cleaned sediments.

24-Funnel-Battery for heavy liquid separations (as fig. 3, p. 53). Constructed of white wood or teak, $\frac{3}{4}$ " or $\frac{5}{8}$ ". Overall length 4' 6", width of base and shelves 10 $\frac{1}{2}$ ", each side 18 $\frac{1}{4}$ " high, lower shelf 11 $\frac{3}{4}$ " up from base, upper shelf 15 $\frac{3}{4}$ " up from base, depth between shelves 4". Each shelf drilled with 24 holes, each 2" in diameter, one hole immediately behind the other, positions of holes in the lower shelf corresponding exactly with those in the upper shelf.

Retort Stand for holding funnels, etc., as fig. 2, p. 43.

Funnels, white glass, short stem, 3" diameter.

Clock-Glasses to cover funnels, 3 $\frac{1}{2}$ " diameter.

Rubber tubing, black, $\frac{3}{8}$ " diameter, supplied by the yard. 1 $\frac{1}{2}$ " sufficient for each funnel.

Pinch-Grips for rubber tubing.

Bottles, odd, coloured glass, for bromoform and solutions; also colourless for the funnel-battery, 24 to each.

Filter Papers, Whatmans No. 41, 11 cms. diameter, supplied in boxes of 100 circles; fan-folded patterns to order.

Hydrometer as specification, page 41.

Hydrochloric acid commercial for cleaning, dilute to 20%.

Caustic Soda, solid, for making N/10 solution.

Bromoform, 2.9 gravity, in 5 lb. coloured glass bottles carefully sealed and packed for export (where applicable).

Benzol, pure, recrystallizable.

Methylene Iodide, 3.3 gravity, in 4 oz. bottles (coloured).

Mercurous Nitrate, 4.3 gravity as fused, in $\frac{1}{2}$ lb. bottles.

See also schedule of equipment given on pages 30, 31, items starred.*

For bromoform recovery from benzol, etc., the following apparatus is essential:—

Engler-type distillation flask, 500 cc. capacity.

Liebig Condenser, glass body with inner tube fused in, 45 cms.

Condenser Stand, universal, with sliding rod and iron clamp.

Thermometer reading to 300° C.
Cork bored to take thermometer.
Wire gauze and Tripod Stand as above.

SINGLE SEPARATIONS. The sample in the first place should be examined with a hand-lens for the detection of the larger and more easily identifiable minerals or micro-organisms, and for those which may be destroyed by subsequent treatment with acid; such minerals as pyrite, limonite and glauconite, together with carbonates and most phosphates are included in this category. A little material should also be mounted dry on a glass slip and examined under the binocular microscope, both by transmitted and incident light. Use a 30-mesh sieve to segregate coarser constituents and operate on all material which passes this sieve. [For discussion of sieving, etc., see p. 110].

The authigenic material coating sand grains is removed by gently boiling with water; in most cases the addition of hydrochloric acid (up to 20%) is necessary to complete clarification, though with exceptionally ferruginous material, up to 50% HCl may be necessary. It is, however, advisable to restrict as far as possible the quantity of acid used and also the time of digestion, since partial destruction of certain minerals is inevitable, and in some cases total decomposition or solution may follow, as indicated above; loss from this cause is anticipated by the preliminary examination of the material as suggested. In the case of calcareous organisms, HCl is obviously impracticable, and the use of strong KOH or NaOH is suggested. This alkaline digest is also applicable with advantage to sediments whose limonitic content is not very great, though it takes longer time for clarification of the grains than does the acid treatment; also to those cases where acid-soluble

minerals are anticipated (as above). When the grains are clear they are washed free of acid with cold water, and then dried slowly in a steam-oven or in a sand-bath.

The next operation involves the use of a suitable "heavy" liquid for concentrating the mineral particles having a specific gravity greater than 2.90, an arbitrary standard, or micro-organisms which, if of calcite, have a specific gravity of about 2.71 or of silica 2.59-2.65. For heavy minerals, of the many liquids advocated and in use, the author favours bromoform (s.g. 2.88 to 2.90, varying considerably in purity) for all general purposes. The objections, that it is liable to excessive convection current effects, rapid evaporation, and that it is expensive to employ, may be met by certain preventive measures. These consist in carrying out the separation in a fume cupboard or constant temperature chamber, or in a room rendered free of warm air currents; also by keeping the bromoform covered when in use with a watch-glass which fits the funnel, and taking care to preserve the benzol washings for the ultimate recovery of the bromoform dissolved; further, the price of bromoform cannot be regarded as prohibitive when compared with the prices of the various other liquids sometimes employed. In the hands of a careful manipulator, 1 lb. of bromoform should be ample for the separation of at least 50 samples, if care is taken to reduce loss to a minimum when recovering the liquid from benzol washings.

For calcite or calcareous organisms, dilute the bromoform with pure benzol (recrystallized) till the specific gravity of the solution is 2.69 (test with a hydrometer). A solution of s.g. 2.45-2.50 will be effective in differentiating quartz and/or calcite

from gypsum, the former species sink, the latter floats. Bromoform may thus be diluted to any strength, giving solutions of decreasing gravity, and by this means specific minerals may be concentrated or diagnosed.

A type of hydrometer most suited to checking the s.g. of bromoform and bromoform solutions is obtainable;¹ it embodies the following essential features :—

Length 20 cms.

Diameter of bulb 2 cms.

Range 2.6-3.0 (or other ranges as desired).

Scale graduated every 0.01 and made as long as possible so that graduations are clear.

Value 2.9 marked in red.

When testing the gravity of a solution, use a 500 c.c. graduated glass vessel. Take care to insert the hydrometer cautiously; do not drop it into the liquid. In diluting bromoform, fill the vessel with sufficient liquid to float the hydrometer at 2.9, then carefully pour in benzol, stirring with a glass rod, until the desired gravity is registered. Both bromoform and bromoform solutions should be periodically checked for specific gravity, stored in coloured glass bottles, kept out of sunlight and *kept cool* (if possible in an ice chest in hot countries). Deterioration is liable to be rapid if these precautions are not taken, especially if bromine starts to separate out. Should the liquid become badly discoloured, try shaking with NaOH or alcoholic KOH, in a separating funnel: the method is not successful in bad cases of deterioration.

Redistillation may be effective, but sometimes leads to a further settling out of bromine or hydrobromic acid.

¹ Messrs. T. O. Blake, 57, Hatton Garden, London, E.C.1

Conversely, recovery of bromoform from benzol-bromoform solution (or benzol "washings"), is achieved by distillation, using an Engler-type flask, 500 c.c. capacity and a Liebig condenser. Benzol boils at 80.5°C and comes over first; bromoform boils at 151.2°C ; it is advisable to keep an eye on the condenser at the higher temperature and stop the circulation of the cold water, if large quantities of liquid are being run through.

In order to economize in the use of "heavy" liquid, take the smallest amount of cleaned sample which is practicable. This implies from 10-15 grs. in the case of average silts (0.05 mm.-0.1 mm. grade), 15-20 grs. of fine to medium sand (0.1 mm.-0.5 mm.), 25 grs. of coarse sand (>0.5); coarse sands and gravels should be panned (the latter screened) to reduce bulk of material; the same applies to clays; see, however, p. 66.

The form of apparatus employed for all separations is shown in the accompanying diagram (fig. 2) and is self-explanatory. The sand is poured into the upper funnel and constantly stirred, at least half-an-hour being necessary to ensure a good separation. It is doubtful whether a 100% separation can ever be effected in practice, but with care it should be reasonably complete. Filtering may in some cases be accelerated by using fan-folded filter papers, obtainable from most makers. Both the light and heavy residues are washed free of bromoform with benzol, and subsequently dried either in a steam-oven or over a sand-bath.

When dry, the residue may be further subjected to special treatment for specific mineral concentration, including magnetic separation and the employment of other "heavy" liquids or fused salts: see pages 56-63.

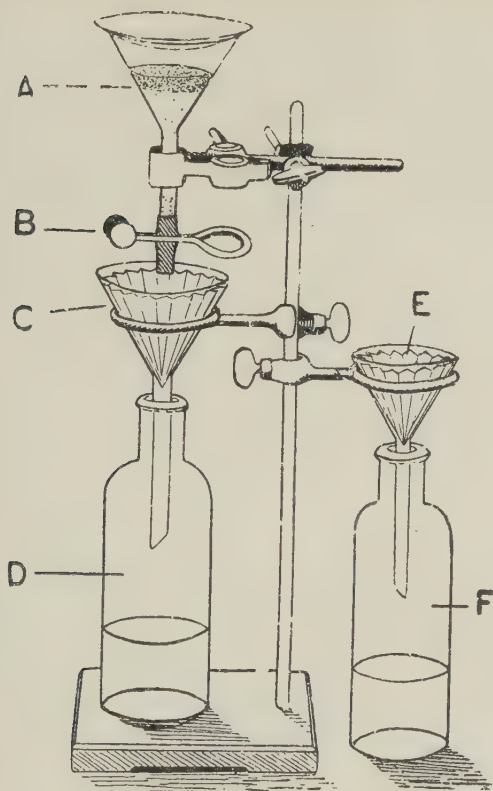


FIG. 2. Bromoform Separation Apparatus.

- A. Funnel containing bromoform and sample from which heavy grains are settling down.
- B. Pinch-cock grip on rubber tubing attached to funnel stem.
- C. Folded filter paper for holding up residue.
- D. Bromoform bottle.
- E. Filter to prevent material from entering F.
- F. Benzol washings bottle.

MOUNTING OF SAND GRAINS FOR MICROSCOPICAL EXAMINATION. The final operation consists in mounting the residue, or concentrated material with Canada balsam on a glass slip, and is similar in many respects to the technique described for thin sections (p. 32), except that it is a little more difficult to attain complete expulsion of air-bubbles. It is advisable to mount the total residue for microscopical examination; by so doing, risk of losing rare species is minimised. The different magnetic crops, if isolated (p. 56), are mounted separately, and a representative sample of the light material may also be mounted. Glass microscope slips (3" x 1") and thin cover-glasses (1" x 7/8") are the most useful sizes. Non-permanent mounts may be made by using ordinary cedar oil, R.I. 1.516; or air-mounts, especially of micro-organisms, may be preferred.

The exclusion of air-bubbles has been mentioned. This process is aided by moistening the cover-glass with turpentine before pressing it down on to the slip; this may be varied by putting the grains on to the moistened cover-glass and then pressing it down on to the slip on which the balsam is sufficiently heated. A little careful "to-and-fro" motion imparted to the cover-glass with tweezers, while the balsam is still hot, is often all that is necessary to obviate the presence of such bubbles.

Solution of the surplus balsam is rapidly obtained as before (p. 34) by using methylated spirit or benzol, a final immersion of the slide in ether being advantageous, but not necessary. Xylol is probably the quickest solvent, but it has an unfortunate habit of eating into the balsam under the cover-glass and thus impairing the mount.

With minerals or rock-fragments capable of passing through a 30-mesh sieve, little difficulty, save with air-bubbles, is experienced in mounting with Canada balsam, but with larger material (+30), unless an inordinate thickness of balsam is used, the method is not practicable. Some workers employ satisfactorily vulcanite rings cemented either by a special gum or with balsam to the slide; more balsam is then put into the ring, together with the material to be mounted, and when cooked, a circular cover-glass is affixed; this is an old method, but one which with care is quite satisfactory, though uncooked or too highly coloured balsam, or air-bubbles, may be troublesome. Another method is to employ microscope slips in which a shallow, bowl-shaped hollow has been ground on one surface; such slips are very useful for air-mounts of *foraminifera*.

A. W. Slocum and E. T. Thomas¹ have devised a neat form of mount which is very useful for micro-organisms and large mineral grains. It consists of a celluloid strip 24 mm. x 60 mm. (of thickness to suit the material) punched at regular intervals by means of an ordinary paper punch giving about 4 mm. holes. The celluloid strip is then cemented to an ordinary glass slip with acetone. Each "cup" thus prepared will receive a grain or organism, which may be cemented in any particular position (if desired), or may be left free as an air-mount. A thin cover-glass, of same length and breadth as the strip, is then cemented on to it with acetone, thus completing the mount. The value of this mount lies in the possibility of preserving on one slide characteristic mineral

¹ *Bull. Amer. Assoc. Pet. Geol.*, 1925, vol. ix., pp. 667-9.

grains of a peculiar assemblage or representative micro-organisms from a particular horizon, etc.

Where a black background is preferred, as is often the case with coloured minerals or *foraminifera*, a similar slide can be made of cardboard suitably punched and glued on to a piece of thin black cardboard of identical size, as described by G. D. Hanna and H. L. Driver.¹ From the point of view of permanence, however, the celluloid-glass combination has much to recommend it.

SYSTEMATIC PROCEDURE FOR SIMULTANEOUS INVESTIGATION OF SAMPLES FOR MICRO-ORGANISMS AND HEAVY MINERALS. The extended use of petrological and micropalæontological methods of subsurface correlation in the principal oilfields of the world during the last few years, has compelled the development of a special technique for handling simultaneously several samples rather than single specimens, as has been customary in the past. This technique, while differing in detail according to local circumstances and demands, is, in its broader outlines, applicable to all large-scale operations of this description, whether of academic or economic purpose. With increased facilities for obtaining rock-samples under practically all conditions of exploratory work, improved methods of preparation and analysis have evolved collaterally, so that the fullest possible stratigraphical evidence may be elucidated from a series of samples with the minimum of time and preliminary treatment.

¹ G. D. Hanna and H. L. Driver, "The Study of Subsurface Formations in California Oilfield Development," 10th Ann. Rep. Calif. State Min. Bureau, vol. x., 1924, No. 3, pp. 5-26.

Apart from the special manipulation of samples for their heavy minerals as a basis of petrographic methods of correlation, the work of palæontologists on the micro-organic contents of such samples (including the *foraminifera*, *diatomacea*, *bryozoa*, *radiolaria*, etc.) as standardized by the geological staffs of oil companies operating in Texas, Louisiana, California and elsewhere, has had a marked effect on the trend of organization of laboratory work for the exhaustive investigation of well-samples. The most detailed, hence the most valuable, *subsurface* stratigraphical evidence to be obtained from any kind of sedimentary rock is that which is compounded of palæontology and petrology; correlation based on one or the other may be entirely satisfactory as a practical expedient and limited to local conditions; correlation based on the cumulative evidence of both lines of investigation carries with it the support of strong scientific probability, is accordingly more exact, and certainly of greater consequence.

Such comprehensive analysis of sedimentary rocks represents the ideal to which all relevant research should tend, though for obvious reasons its attainment is largely restricted to those spheres of oilfield activity where highly trained technical staffs enjoy full laboratory facilities for the prosecution of such work; with a more general appreciation of the principles and methods involved, however, it is certain that they will be more widely adopted, not only under oilfield conditions, but equally in all phases of sedimentary petrological research.

Pursuing each line of investigation exclusively, implies independent treatment of separate portions of a sample for its heavy minerals and its micro-fossils, a duplication of pre-

paratory work which is an unnecessary waste of time. The development of a systematic procedure for simultaneous extraction of both constituents became, therefore, a desideratum, especially in large-scale work, and a few attempts to formulate such a plan were made by American workers with varying degrees of success, in particular that devised by G. D. Hanna and H. L. Driver.¹

Experience with all kinds of rocks, surface samples, oil-well samples, cores, "cuttings" and the like, has resulted in the adoption by the author of the procedure detailed in the following paragraphs. This plan of operation has the advantage that, although it makes for routine practice which can be carried out by non-technical assistants under supervision, it is sufficiently elastic at critical stages to be adaptable to special circumstances which may arise during the course of investigations. The ultimate success of this procedure depends to some extent, however, on the initial measures adopted for classifying the samples, not only as a basis of their comprehensive analyses, but also for purposes of collateral and future reference; accordingly some system, such as that already described for filing information (pp. 21-23), is an essential preliminary to this technique.

Before proceeding with the treatment of the samples, the batch should be arranged in definite order; they should not be selected indiscriminately. With samples derived from the same well, the series should be made up in ascending or descending order according to depth, the deepest being taken first, and working gradually upwards to those nearer the surface, or *vice versa*; where investigations are proceeding collaterally with the

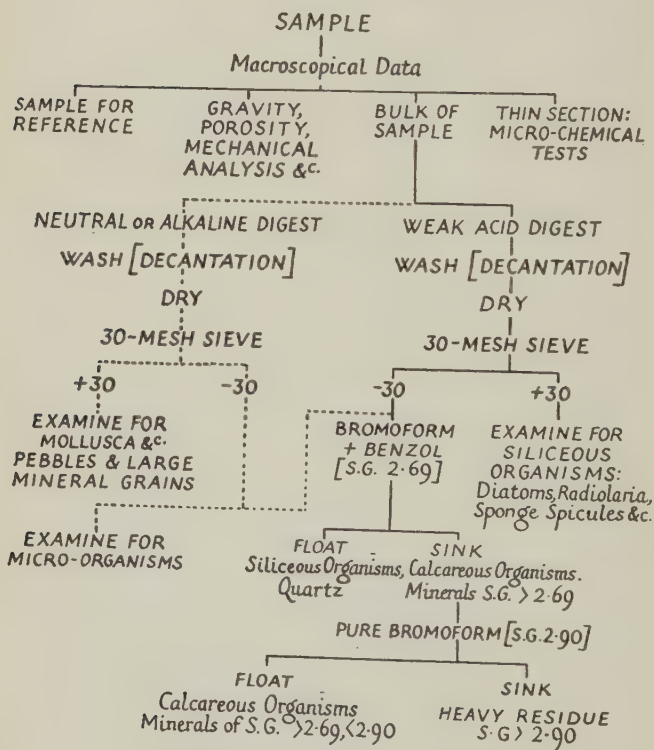
¹ *Op. cit.*

drilling of the well, as is often the case, obviously the reverse order will be maintained, each batch of samples being dealt with in order of depth as they are received from the well. With outcrop samples some similar system should be adopted, implying a geographical sequence, *e.g.*, direction of traverse, strike direction, vertical sequence (quarry-face, cliff-section, etc.), stratigraphical sequence, and so on. The advantage of such orderly procedure will be readily appreciated when the treatment of a series of related samples is contemplated, since connected results automatically emerge as the work progresses.

The "flow-sheet" (p. 50) shows in tabular form the plan of procedure. Where only heavy mineral concentrates are sought, the standard methods of separation previously described hold good, though modifications in apparatus for dealing with a number of samples at the same time are noted below (p. 53). Where organisms only are required, and where it is desired to segregate calcareous and siliceous forms, the procedure need only be followed as far as the bromoform-benzol stage, though final treatment with bromoform to get rid of heavy minerals, especially if much pyrite occurs (p. 65), is often advantageous. Samples which are impregnated with petroleum residues require special treatment at the outset (p. 70).

Macroscopical Data. (See also pp. 25-29). In the first instance the sample is spread out on white paper or in a large shallow evaporating basin for macroscopical examination, aided by hand-lens. A record is then made of the colour, lithological nature, pebble constituents and shell-fragments (if any), etc., etc., which may be apparent. Approximately three-quarters of the sample is then taken to constitute the "bulk-sample"; the remaining quarter is divided into a portion for reference ("key-sample"); a portion for physical tests if desired (*e.g.*, specific gravity, porosity, mechanical analysis), and, if required and prac-

SYSTEMATIC PROCEDURE FOR SIMULTANEOUS ANALYSIS OF SEDIMENTS FOR MICRO-ORGANISMS & MINERALS..



licable, a suitable piece is selected for thin section preparation which, apart from the microscopical examination in the usual way, can subsequently be utilized for any particular micro-chemical tests; in the case of physical tests, where these are of paramount importance, probably more than the suggested amount (25%) of the original sample will be utilized: it depends largely on the quantity of the sample initially available.¹

With core-samples and compact rocks such as shales, mudstones, etc., it is necessary to break these down before proceeding, bearing in mind, in the case of core-samples, the precautions already noted (p. 17). Such disintegration can generally be accomplished by splitting the material parallel to any prevalent lamination or bedding and then crumbling the laminæ or fragments thus obtained with the fingers or with the aid of a pestle and mortar; drastic pulverization is to be avoided wherever possible. In refractory cases, several methods have been devised to promote disintegration; heating the sample to redness and then plunging into cold water is one common method; other methods consist in boiling the fragments with caustic soda; in covering the crushed sample with an equal amount of sodium acetate, adding a few drops of water and heating, when the crystals melt; the sample becomes saturated with the solution, and, on cooling, the addition of a crystal of the acetate causes crystallization; the force thus exerted determines the disintegration of the rock particles;² a similar result can be achieved by the use of sodium thiosulphate.³ An application of Mann's method⁴ of disintegrating diatomaceous shales also suggests itself: this consists in boiling the fragments for a few moments with sodium carbonate solution and then quenching with HCl; the evolution of CO₂ has the effect of breaking down the shale successfully.

"Bulk-Sample." The "bulk-sample" is divided into two portions, one digested with weak hydrochloric acid (up to 20%): "acid digest"; the other is treated with H_2O

¹ For relevant methods and calculations, Holmes' "*Petrographic Methods*," 1921, chs. 2 and 5, should be consulted.

² M. Guinard, *Journ. Queckett Micros. Club*, 1888, Ser. 2, vol. iii., p. 188.

³ G. D. Hanna and H. L. Driver, *op. cit.*, p. 14.

⁴ A. Mann, *Proc. U.S. National Museum*, vol. lx., 1922, pp. 1-8.

caustic soda : "alkaline digest." If known to be rich in calcareous organisms, treat the major part of the sample with alkali. In both cases gentle though possibly prolonged heating accomplishes clarification, and, in the case of the acid, removal of soluble minerals and calcareous organisms which, however, are preserved in the alkaline digest.

Acid Digest. The authigenic material, mud or scum resulting from this digestion is washed away with cold water by decantation, the remaining portion being dried over a sand-bath or in a steam-oven. When dry and cold, it is passed through a 30-mesh sieve; the +30 material is examined carefully for the larger siliceous organisms (diatoms, *radiolaria*, sponge spicules, etc.), significant rock-fragments, pebbles or mineral grains; large constituents are picked out by hand or with tweezers, the smaller organisms, etc., with a camel-hair brush moistened with glycerine or cedarwood oil, usually under a strong hand-lens. The -30 material is next transferred to the bromoform-benzol solution of specific gravity 2.68—2.70. This solution serves to float off the smaller siliceous organisms and the light minerals (including quartz) of specific gravity <2.68—2.70. The material which sinks is the heavy mineral residue plus any calcareous organisms which may have escaped destruction by the acid treatment.

Alkaline Digest. The alkaline treatment serves to clarify the other portion of the "bulk-sample" and aid the detection of calcareous organisms; incidentally, it helps in disintegrating the particles if there has previously been some difficulty in doing this. The scum is again washed off by decantation, taking care not to lose anything but the muddy matter, and the residue dried over a sand-bath as before. It is then passed through a 30-mesh sieve; the +30 material is segregated and examined for the more prominent pebble constituents, large mineral grains, molluscan or other fossil organisms, which may be separated by hand as with the similar product from the acid digest. The -30 material is next added to the -30 material from the acid digest, and the whole passed into the bromoform-benzol solution; or, if preferred for any particular reason, the bromoform-benzol concentration may be carried out separately on both lots. As explained above, this solution has the effect of floating off the light minerals (quartz), and the siliceous organisms which can thus be easily concentrated; calcareous organisms, preserved by the alkaline digest, are left behind with the normal heavy mineral suite.

Some difficulty may be experienced at this stage in getting the calcareous organisms to sink completely if, in the case of *foraminifera*, the previous treatment has resulted in the cells filling up with air; this can to a large extent be overcome by very complete stirring and by constantly depressing the material with a glass rod well into the solution.

Bromoform Separation. The last stage in the process consists of floating off with bromoform (s.g. 2.9) the calcareous organisms (*foraminifera* particularly) and minerals of specific gravity $>2.68-2.70$ and <2.9 from the ultimate heavy mineral residue (>2.9) used in petrographic methods of correlation. Thus a microscope slide of the "light" material will consist principally of a concentrate of calcareous organisms *minus quartz*, the desired end in view, since it saves the necessity of tedious hand-picking of minute bodies under the microscope.

Simultaneous separation of at least two dozen concentrates (either with the bromoform-benzol solution or with bromoform alone) is achieved by the use of a funnel-battery capable of holding 24 funnels with corresponding drainers as shown in fig. 3. Two of these batteries side

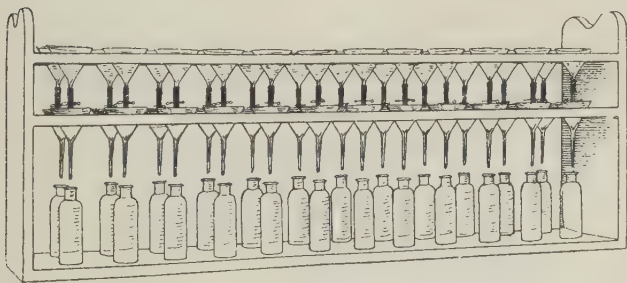


FIG. 3. Funnel-battery for Bromoform Separation.

by side are employed, one for the bromoform-benzol separations, the other for the normal bromoform separations, the concentrates being passed on from the first to the second automatically. Those accustomed to carry out single bromoform separations will readily appreciate the great sav-

ing of time and labour afforded by such large-scale operations. It may be argued that bromoform is expensive to use in this way, but 2 lbs. of the liquid will be ample to fill 24 funnels with an adequate amount, and ultimate loss through volatilisation is not much greater, if care be taken, than when using the same amount for successive single separations; also, the use of bromoform on this scale adds considerably to the quantity of bromoform washings (in benzol) at any one time, so that it pays to redistil the washings for recovery of the heavy liquid at the end of a day's run. The supervision of two of these funnel-batteries in simultaneous operation renders it possible to dispose of well over one hundred samples in a comparatively short time.

At first glance the foregoing procedure may seem somewhat complicated, but a trial will prove its efficacy and comparative simplicity of operation. It is not contended that the plan is an infallible one, or that cases do not arise where certain departures from the routine may be desirable; but where separate concentrations of groups of organisms and heavy minerals are required from a number of samples with some degree of rapidity, the procedure has much to commend it. Its success is more readily assured by having the requisite apparatus always handy, keeping special dishes, sieves, etc., apart for the two different digests; apparatus used for the alkaline treatment may be conveniently designated with a blue mark on each article, that for the acid digest, with a red mark; in this way confusion of products is avoided during operations.

The acid and alkaline solutions should be made up ready in Winchester Quart bottles and suitably labelled; sufficient bromoform-benzol solution should be made up for one batch of samples at a time, and not in too great a bulk, since it is liable to deteriorate on keeping, as already mentioned (p. 41). The real secret of successful

work on these lines lies in the establishment of the necessary organization, including equipment, under which the several operations can be carried on uninterruptedly; shortage of apparatus, intermittent attention, incorrect solutions (as regards gravity), or, what is worse, inability to "keep one's head," are one and all certain causes of failure.

Special Methods of Concentration.

PANNING. Where the initial bulk of a sample is greater than that desired for heavy mineral analysis, it may be conveniently reduced by the ordinary process of panning under running water in a wide, open tray, developing dish or evaporating basin. The secret of success here lies in the ability to give a combined circular and "to-and-fro" motion to the water; this has the effect of swirling out the lighter and finer constituents, which are carefully poured off, and concentrating the larger and heavier grains. Skilful panning should not result in any appreciable loss of heavy mineral.

Exactly the same process is carried out when operating on fine grained rocks, *e.g.*, clays, shales, etc., and crushed rocks; see pages 73-75. It has also been used with some degree of success in cases where heavy liquids have not been available for mineral concentration.

SIEVING. Further remarks under this heading will be found in Chapter V on Quantitative Methods, p. 110. For ordinary qualitative work it suffices to use a standard I.M.M. 30-mesh sieve and to neglect, for concentration, all material held up thereby. Other useful sizes in this connexion are 60- and 90-mesh. Sieves are only capable of a crude grading, but they are rapid and convenient. If they get choked up with fine material, give them

some sharp taps upside down on the floor; this usually has the desired effect. *If necessary clean a sieve with fluid, use methylated spirit or ether, not water.*

ELUTRIATION. Elutriators have been employed with advantage for concentrating both micro-organisms and heavy minerals in certain samples where either or both constituents are known to conform to limited grades. It is found that, in such instances, the bulk of the desired grains or organisms may be segregated by specific velocities of an upward-moving current of water. If a standardized single vessel elutriator is handy (fig. 4), this method is worth a trial. Quantitative aspects of elutriation (for mechanical analysis) and references to technique are given in Chapter V, page 108.

MAGNETIC SEPARATION. Magnetic separation of the heavy residue is frequently desirable, the strongly magnetic species being extracted with a bar magnet, or a horseshoe magnet having adjustable pole-pieces; care should be taken to place a thin sheet of paper between the poles of the magnet and the residue. Further separation may be effected by using an electro-magnet whose intensity may be varied (within certain limits) by altering the resistance of the current; in this way moderately magnetic and weakly magnetic minerals may be isolated from both strongly and non-magnetic species.

"Where provision for an electro-magnet cannot be made, this is a far more convenient and flexible apparatus with which to work, since magnetic intensity can be made to vary with the resistance of the current used, with the distance between the pole-pieces, or according to the space allowed between the ends of the pole-pieces and the con-

centrate. In this way a concentrate, whose strongly magnetic minerals have already been

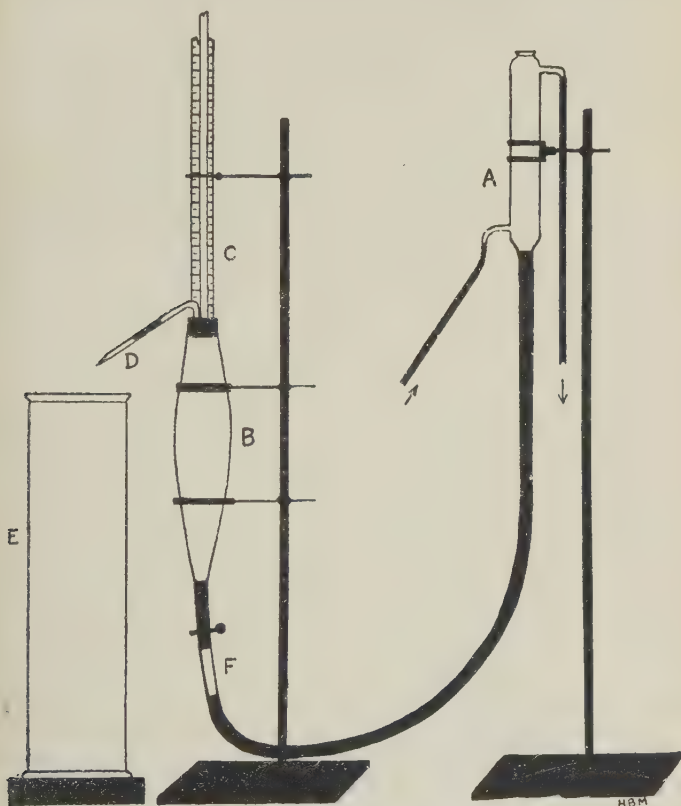


FIG. 4. Single Vessel Elutriator.

abstracted with a bar or horseshoe magnet, may be divided into moderately magnetic, weakly magnetic and non-magnetic crops, or, of course, the

electro-magnet may be used for the entire separation. It will be found that repeated searching of the crops with the magnet is necessary to arrive at cleanly segregated groups, and the achievement of the four distinct grades, strongly magnetic, moderately magnetic, weakly magnetic and non-magnetic, is not as easy as would appear at the outset, largely for the reason that the minerals themselves vary considerably in their magnetic properties, even similar species in the same concentrate.*

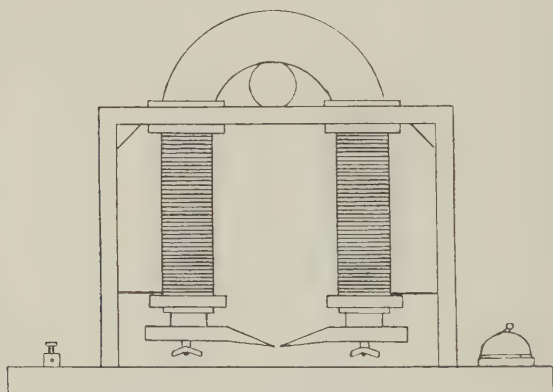


FIG. 5. Electro-magnet.

“Electro-magnets are made to several designs, but the principle of all patterns is much the same. Fig. 5 shows one satisfactory type employed by the authors.

“The current is supplied either by an accumulator, suitable battery or direct from light

*This, and the succeeding paragraphs on Electrostatic Separation, Dielectric Separation and Vibration Methods, are taken from “*Alluvial Prospecting*,” by C. Raeburn & H. B. Milner (1927), pp. 238-243.

or power supply, in which case an adequate resistance must be placed in the circuit. If electric lamps wired in parallel are used for this purpose, the resistance can be altered by decreasing or increasing the number in circuit, resistance (ohms) varying inversely, and current (ampères) directly as the number of lamps employed; the lamps should each be of similar candle-power or watts. Alternatively, a suitable rheostat may be used for controlling the resistance. The design of electromagnet chosen will, to a great extent, depend on the nature of the separations which will commonly be made, the power available, and other local circumstances.

“ELECTROSTATIC SEPARATION. Minerals which are good conductors of electricity may often be extracted from a concentrate by means of a glass rod in which a charge is induced by rubbing with silk (+), or ebony or sealing-wax rubbed with cat-skin or rough flannel (—). The application of this well-known principle was developed in connexion with mineral separation by T. Crook some years ago.¹ His apparatus consists of two copper plates, one supported above the other; the upper one has its under-surface coated with a thin layer of shellac ‘which should be continued over the edge of the plate so as to form a narrow strip around the margin of the other face. At or near the edges of the shellac-covered face there should be insulating supports, which may conveniently be made of two narrow strips of glass cemented to the plate and coated with shellac.’ This upper plate, with its supports, is placed on a lower naked copper plate, on which the mineral grains are first placed.

¹ T. Crook, “The Electrostatic Separation of Minerals,” *Mineralogical Mag.*, xv., 1909, p. 260; xvi., 1911, p. 109.

On charging the upper insulating plate with the aid of an electrophorus—providing the minerals and the whole apparatus are absolutely dry—the good conductors are attracted to the shellac-covered surface of the top plate, from which they are ultimately removed by lifting the plate and brushing the grains off the lower surface. In this way the non-conductors are left behind on the bottom plate; such a concentrate ‘can be finally cleaned as far as possible by the sealing-wax method, which offers fuller control.’ Electrostatic methods of separation are extremely useful in isolating such minerals as ilmenite, magnetite, wolframite, columbite and tantalite from cassiterite (sometimes a moderate conductor), quartz, zircon, monazite, apatite, etc.

“DIELECTRIC SEPARATION. Prof. B. W. Holman has within recent years carried out research on the Hatfield process of dielectric separation as a factor in mineral concentration.¹ To some extent the application of the principles involved is still in an experimental stage, though the following possibilities are now realized:—

(i) The separation of good conductors from bad ones of low dielectric constant, *e.g.*, finely disseminated zinc blende from galena, metallic silver from vein-material.

(ii) The separation of earthy minerals of low dielectric constant from one another or from gangue material, *e.g.*, oxides of Ni, Co, U, Vd, Ce, Th, and such minerals as gadolinite, phenacite, carnotite, etc.

(iii) The treatment of tin ores, especially when cassiterite is of very fine grade.

¹ *Mining Mag.*, vol. xxviii., 1923, p. 267; *ibid*, vol. xxx., 1924, pp. 132, 181; also *Bull. Inst. Min. Met.*, 1924, pp. 335-370.

(iv) The separation of heavy minerals from a concentrate of a particular species which is a good conductor or which possesses a fairly high dielectric constant, *e.g.*, thoria and ceria from tin concentrate.

“It is apparent that under certain conditions the methods are applicable to mineral concentrates, especially if these are of fine grade. Briefly, the method consists in using a grating immersed in a suitable liquid (whose dielectric constant falls between that of the two minerals it is desired to separate); the parallel bars of the grating are alternately connected up to the two ends of an alternating current, 200-250 volts; the mineral possessing the higher dielectric constant is attracted to the bars, that with the lower dielectric constant being repelled. An example is furnished by quartz and cassiterite: the latter has a dielectric constant (50) and is attracted, while quartz (4.5) is repelled if the grating is immersed in aniline (7.3), amyl alcohol (16) or nitrobenzene (36). ‘Minerals which differ from one another in dielectric constant by as little as a whole unit can be so separated if their dielectric constants be below 60.’ The following table of dielectric constants is quoted from Holman’s paper :—

TABLE OF DIELECTRIC CONSTANTS.

Solids.		Liquids.	
Eleonite	2.5	Kerosene	2.0
Sulphur	3.0	Benzene	2.3
Quartz	4.5	Carbon disulphide	2.6
Rock Salt	5.6	Aniline	7.3
Fluorite	6.8	Acetylene tetrachloride	10.0
Calcite	7.5	Amyl alcohol	16.0
Mica	8.0	Ethyl alcohol	26.8
Blende	40.0	Ethylene dichloride	18.0
Cassiterite	50.0	Methyl alcohol	35.4
Magnetite	over 50.0	Nitrobenzene	36.0
Rutile	over 50.0	Water	70.0

(See note, p. 62).

" It should be remembered that these figures vary with the frequency employed also that, for some of them, different authorities give very different figures.

" For further particulars of this process, reference should be made to the papers cited.

" **VIBRATION METHODS.** Some years ago a method was developed for separating certain minerals by induced vibrations, more particularly cassiterite, wolframite, columbite, etc., from vein-quartz or gangue (in the crushed state). The principle depends on imparting frequency to a sheet of paper or a thin metal plate on which the minerals have been placed. The paper or plate is held in suspension horizontally at one end by the left hand, and the necessary vibrations set up by regular tapping with a pencil or a hard instrument with the right hand; alternatively, a thin metal plate is clamped at one end and made to vibrate by resonance, using a tuning fork of suitable pitch; the frequency of vibration depends on the thickness of the plate and the point at which it is clamped. The method is not one of universal application, but with certain concentrates (only ascertainable by trial) it works well.

" When employing vibratory methods of concentration, it is found that if a highly glazed paper or well polished copper or brass plate be used, separation is considerably facilitated; also, minerals possessing a large surface-area in proportion to their thickness, *e.g.*, mica, lag behind the more irregularly shaped (and often heavier) species; thus the method is useful for getting rid of excessive mica, light particles of foreign matter, dust, etc., though it should be pointed out that the principle involved in the latter cases is that of retardation due to friction rather than to the

periodicity set up in the supporting medium and imparted to resonant grains."

USE OF OTHER HEAVY LIQUIDS AND FUSED SALTS. If it is desired to segregate a particular mineral of given specific gravity from the residue, the use of other liquids may be necessary; those most easily manipulated are mercuric potassium iodide (3.18), cadmium borotungstate (3.28), methylene iodide (3.3), fused mercurous nitrate (4.3), thallium silver nitrate (4.50), and thallium mercurous nitrate (5.30); the iodides require washing with benzol, and the salts with water. Iodide separations are most conveniently carried out in a shortened boiling tube, the excess of liquid with the lighter particles being poured off into a small basin; alternatively an ordinary separating funnel may be employed. Mercurous nitrate and other fused salt separations are made in a test tube, the salt and the residue being heated together over a bunsen burner; in the fused state, gravitational separation occurs, the lighter particles floating to the surface of the melt. On cooling, solidification ensues, the tube is broken and the "heavy" mass isolated from the lighter by cutting the salt with a knife. The grains are ultimately recovered by dissolving the mass in water. *Fig. 6*, taken from "*Alluvial Prospecting*," serves to illustrate the method.

DETRITAL MINERAL CONCENTRATION BY HAND. This very tedious, but often necessary operation, is frequently found to be the most rapid method in the long run of obtaining reasonable concentrates of one particular species from a heavy mineral segregation. Minerals possessing some specific property whereby they can be cleanly selected by one of the processes just described, naturally need

no special picking out, but in cases of desired concentrates of such species as epidote, staurolite, pyroxene, serpentine and many others, especially where these minerals are not very prolific in the residue, they will, in ordinary circumstances, have to be isolated by hand. This form of hand-sorting is best carried out with a camel-hair brush of fine point moistened with cedarwood oil or glycerine,

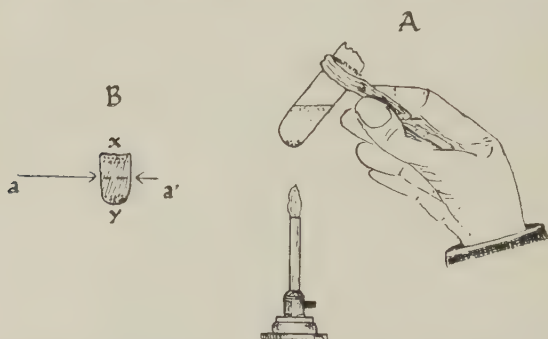


FIG. 6. Diagram to illustrate the use of Fused Salts in Mineral Separation. A, in fluid state with minerals separating out; B, solidified core recovered on cooling; the core is cut along the line a—a', the lighter minerals being held in the part x, the heavier being contained in y.

and the segregation is made under the microscope, using low power magnification and good transmitted light. As picked out, each grain should be placed in a suitable receptacle; a glazed porcelain tile with twelve or sixteen hollows, as employed for colour-testing in quantitative chemical analysis, answers admirably.

ELIMINATION OF PROLIFIC MINERALS FROM HEAVY RESIDUES. Core-samples, especially those composed of clay and shale and taken from some depth below the surface, frequently present over-

whelming quantities of minerals such as pyrite, pyrrhotite, gypsum, etc., which, by masking the less frequently occurring non-opaque species, may render identification and assessment of these a matter of extreme difficulty, so that the residue becomes practically worthless from a petrographic standpoint. Such minerals, once recorded, are best removed; sometimes the initial acid digest does this automatically, but more often than not these minerals find their way into the bromoform residue, and have, in consequence, to be eliminated.

Pyrite is best got rid of by digesting the heavy residue with weak nitric acid (up to 15%); gentle warming may be necessary. It should be borne in mind, however, that certain other minerals present, *e.g.*, apatite, are liable to attack from this treatment; to safeguard the possibility of thus losing minerals, a mount of the original residue should be made as an initial check.

Pyrrhotite is soluble in hydrochloric acid, and can thus be eliminated. Much of this mineral is, however, destroyed by the first acid digest.

Gypsum is a frequent constituent of clay and shale, and may be very troublesome in oil-well samples. Because of its low gravity (2.3) it should not appear at all in the bromoform residue, though sometimes, owing to abundant inclusions of iron-ore, it does come down with the heavy suite. It is generally eliminated by the bromoform-benzol solution; it may be attacked by hydrochloric acid; drastic treatment consists in digesting with a strong ammoniacal solution of ammonium sulphate.

Anhydrite has a higher gravity than gypsum (2.9—2.98) and where prolific can be removed with hot, strong hydrochloric acid.

Barite. This mineral is liable to give similar trouble, though it is less frequent in occurrence than pyrite and gypsum in petroliferous rocks; it is not uncommon, however, in sediments associated with saline deposits, or in porous sandstones of terrestrial origin in which it acts as a cement; or it may be introduced as a heavy drilling mud. Its elimination can be effected by hot concentrated sulphuric acid in most cases, but the treatment is drastic and may affect other minerals present.

Pyrolusite, for the most part exceedingly local in sediments, may if necessary be removed by digestion with strong hydrochloric acid (warm).

Cloudy Aggregates attached to certain minerals in the form of a film, thus masking the nature of those minerals, may sometimes be removed by nascent carbon dioxide; any violent effervescence may be equally effective, especially with non-ferruginous compounds such as kaolinite, carbonates, etc. This treatment is not infallible, however.

Treatment of Argillaceous Rocks. Clay, marl, extremely fine silt and similar material require substantially different treatment for extraction of accessory minerals, from that involved in the case of coarser detritus. Some examples, when dry, are extremely difficult to "break down" under water, though a few drops of ammonia or 10% solution of Na_2CO_3 may be effective in this respect. Professor Boswell has described a neat method of making the sample practically red-hot, and then plunging it into cold water, to obviate the difficulty; but even this is not always successful, and a very gentle pulverization in a mortar may be necessary. Other methods applicable have already been described (p. 51).

An initial concentration may be obtained by repeated washing with water, in much the same way that panning of sands is carried out (p. 55); the resulting material may have to be cleaned with weak acid, but in many instances this proves unnecessary. When dry, a bromoform separation may be tried, and if the grains are not too small, it may be successful. The author has found, however, that grains of average grade-size, <0.01 mm., will not respond readily to such separation, owing to surface tension effects, and in such cases recourse has to be made to other methods. A somewhat tedious way is to mount up several slides of the concentrated material and differentiate

under the microscope between the essential and accessory minerals. Elutriation may be resorted to, in order to produce a series of graded crops of minerals which may be mounted for examination under the microscope. It is frequently found that concentrations of the "heavy" minerals occur with two or three definite grades, and this facilitates their study, but the method is by no means infallible and will most certainly fail with very fine material. Generally speaking, the accessory minerals, as also any detrital quartz present, conform to rather larger grade-sizes than does the clay-substance when pulverized, and accordingly it is seldom that one or other of the above methods fails to produce the desired mineral crop. In really stubborn cases, however, the problem would seem to be only capable of solution by the aid of a centrifuge, and work is in progress to test the possibilities of this application.

Shales, mudstones, consolidated marls, and similar fine, compact rocks, are treated as crushed samples according to the methods described on page 73.

Treatment of Calcareous Rocks. The extraction of heavy mineral residues or of any detrital mineral components from limestones and allied types is not a difficult matter, and proceeds either according to the methods described for crushed rocks (p. 73), which is usual, or alternatively acid solubility is made use of, and the detrital constituents separated with bromoform from the inorganic residuum left; this last method applies more particularly to soft limestones, oozes and similar materials; most calcareous rocks are hard and compact and need a degree of crushing before they can be treated for mineral concentrates.

Treatment of Carbonaceous Rocks. The microscopy of coal usually concerns the nature and origin of vegetable structures or coal-substance, and, as such, lies outside the scope of petrology. Consequently few but palæobotanists are inclined to probe coal-sections deeply; mineralogical evidence is subsidiary to the more fundamental study of the hydrocarbon. Coal may, however, yield heavy mineral assemblages at least as definite and varied as those obtained by panning clays, for instance; not merely ubiquitous pyrite or marcasite, but the more stable detrital constituents may be released by combustion or solution of the organic matter. This phase of investigation was first suggested to the author by Professor W. W. Watts some years ago, since when experiments have been made from time to time on various coals (including lignite) and coal-ash, with interesting though possibly limited results.

The coal substance may be eliminated by burning the coal to ash, washing (by which means much of the light "flaky" matter is disposed of) and drying, then examining microscopically the residue which may be further concentrated by bromoform if desired. The high temperature of combustion is, however, liable to destroy certain minerals. Alternatively the solution method, using aqueous caustic potash, pyridine, phenol, chloroform, or sodium hypochlorite has been successfully employed with different types of coal, though some varieties are stubborn (hard bituminous coal and anthracite); gentle pulverization before solution is necessary.

The average inorganic residue (ash) of coal is seen to consist of quartz (often iron-stained), black particles of metallic ore (some of the latter possibly unburned or undissolved carbon), scaly micaceous

matter, and stable accessory minerals such as tourmaline, garnet, zircon, rutile; such minerals sometimes resemble those extracted from associated ganisters or grits, or may be quite different, a point of some theoretical significance; other samples have yielded zinc and copper ores. On searching the literature we find that Stutzer¹ records the occurrence of millerite, cinnabar, chalcopyrite, sphalerite, galena, malachite and molybdenite in coal; gold has been found in the coal of Cambria, Wyoming;² silver has been observed in black carbonaceous shale;³ vanadium occurs in coal-ash from Scotland,⁴ in peat-ash from North Carolina,⁵ in lignite from San Rafael, Mendoza, Argentine,⁶ and in coal from Yauli, Peru;⁷ uranium was detected by Nordenskiöld in an "anthracitic bitumen" from Sweden,⁸ and by Liebert in the "Kolm" of that country;⁹ radium has been discovered in certain Alabama coals.¹⁰ Although in some of these cases the elements have only been detected during the course of quantitative chemical analysis, the records clearly indicate possibilities of mineralogical interpretation by microscopical examination.

¹ Kohle (*Allgemeine Kohlengologie*), Berlin, 1914, pp. 19, 193.

² R. W. Stone, *U.S.G.S.*, Bull. No. 499, 1912, p. 63.

³ T. A. Rickard, *Trans. Amer. Inst. Min. Eng.*, vol. xxvi., 1896, p. 978.

⁴ J. C. H. Mingaye, *Rec. Geol. Surv. N.S. Wales*, vol. vii., 1903, p. 219.

⁵ C. Baskerville, *Journ. Amer. Chem. Soc.*, vol. xxi., 1899, p. 706.

⁶ J. J. Kyle, *Chem. News*, vol. lxvi., 1892, p. 211.

⁷ *Journ. Chem. Soc.*, vol. lxx., 1896, pt. ii., p. 252.

⁸ *Compt. Rend.*, vol. cxvi., 1893, p. 677.

⁹ C. Winkler, *Zeitschr. Kryst. Min.*, vol. xxxvii., 1903, p. 287.

¹⁰ S. J. Lloyd & J. Cunningham, *Amer. Chem. Journ.*, vol. l., 1913, p. 47.

Geologically, the significance of the petrography of coal attaches to the possible indication afforded of its mode of origin; the detrital constituents when localized may suggest direction of transport, hence "drift coal," or "growth-in-situ" may be indicated either by impoverishment or absence of such minerals, or by close resemblance of an assemblage to that of intimately associated measures. The potentialities of this phase of petrographic work are obvious, but too much must not be expected of it, especially with bituminous and anthracitic coals. Terrestrial peat, certain lignites and brown coals, and especially estuarine coals, form the most encouraging materials to work on. For further data, see Chapter VII, p. 264.

Oil-shales, asphalts, asphaltic rocks and various bituminous substances are similarly interesting, the mineral accessories extracted often being sufficiently well individualized to warrant their use as indices of provenance of the material, direction of flow of the bitumen, manner of impregnation, and so on. From another standpoint the presence of rare minerals or elements in such substances may attest the action of bacterial or other organisms possessing specially selective or segregative powers, thus throwing light on the complicated mechanism of the genesis of these substances; vanadium minerals in Trinidad "manjak," and in the "grahamite" of Page, Oklahoma, are cases in point.

Treatment of Impregnated Samples. Oil-saturated sands, if the hydrocarbon is in a fluid state, can be clarified by repeated digestion of the sample with cold (sometimes warm) benzol, chloroform, ether or carbon bisulphide. If, however, impregnation is of a solid asphaltic character, it is

necessary to employ a reflux condenser (fig. 7) for its removal, this operation often taking several

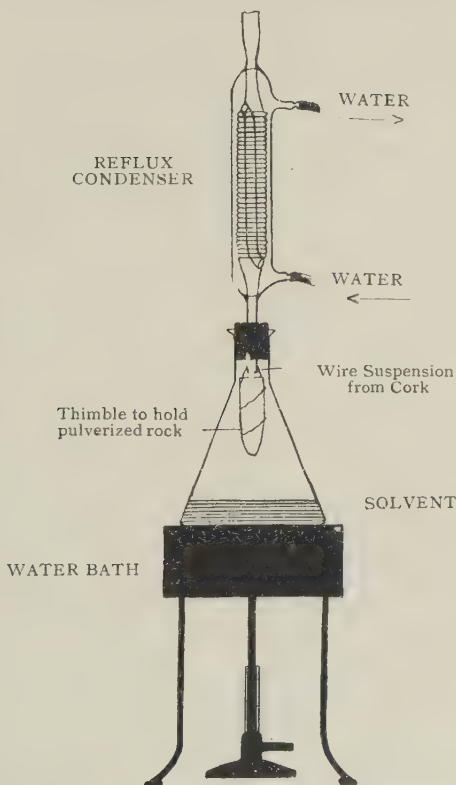


FIG. 7. Reflux Condenser for Bitumen Extraction.

hours for its complete achievement; one or more of the liquids mentioned are used.

In no circumstances should a sample containing petroleum or petroleum residue be pro-

ceeded with for heavy mineral analysis as previously suggested, unless such extraction has been carried out, as the presence of the hydrocarbon will discolour and render useless not only bromoform-benzol solution, but bromoform itself, and recovery of such contaminated bromoform is a very long and uneconomic process; the hydrocarbon also tends to coat individual particles, thus rendering their identification almost impossible. A further difficulty results from the tendency of such impregnated rocks to flux with Canada balsam during the process of making the microscope slides (p. 35).

The extraction apparatus is very simple to set up and to operate. The thimble is two-thirds filled with the sample from which the coarser (pebble) constituents, if any, have been previously removed. It is attached by means of a wire to the cork, and so held in place in the neck of the flask as shown; the cork is covered with "silver" paper to prevent any detached particles falling back into the thimble. About 1-1½ inches' depth of solvent is usually ample; a start should be made with benzol which, in the case of strongly impregnated rocks, may be followed by the successive use of chloroform, ether and carbon bisulphide, until complete clarification is obtained. Thereafter the sample is submitted to alkaline and/or acid digest in the manner previously described. It will be evident that this method of extraction of the hydrocarbon can be made quantitative if desired, percentage impregnation being determined by using initially a known weight of rock, subsequently calculating on the basis of the weight of clarified sample remaining after treatment, checked by the weight of recovered hydrocarbon obtained by evaporating the solvent to dryness. [N.B.—By connecting up

a series of reflux condensers, two or more samples can be clarified in one operation].

Another method is available for extracting mineral particles and other inorganic matter from solid asphalts and bitumens. This consists in dissolving a given quantity of the substance in sufficient solvent, carbon bisulphide, carbon tetrachloride or petroleum naphtha, and filtering the solution through a Gooch crucible fitted with an asbestos pad; the crucible is retained in a pressure flask connected to a vacuum pump in the usual way. The mineral particles, etc., will be left behind on the asbestos pad, from which they can be easily recovered by washing with some of the solvent used. This is a very rapid and effective method, but it is not applicable in cases where the inorganic content is high; such cases must be dealt with by the extraction methods above described.

Crushed Rocks. Compact, consolidated sediments such as sandstones, grits, quartzites, shales, mudstones, ironstones and the like, are normally studied by means of thin sections cut from the samples, as with igneous rocks. But just as the minor accessory minerals frequently escape detection in thin sections of the latter, so it is with sedimentary types, and for this reason the supplementary practice of microscopical examination of the crushed material is carried out.

The methods, applicable alike to igneous, metamorphic and sedimentary rocks, consist in crushing the sample in a steel mortar until pulverized, avoiding the formation of rock-flour as far as possible. The powder is then panned in water in a 10-inch evaporating basin, and in this way the finer light material may be eliminated and the heavier fragments concentrated at the bottom of the dish. As it is often necessary to treat

several pounds of rock before an adequate concentrate is obtained, repeated panning is resorted to, using more than one dish at first, but gradually reducing the quantity of material until it can all be concentrated in one receptacle. Panning is, of course, inadmissible in quantitative work; in this case, the powder is poured into a beaker of water, stirred, then allowed to settle; the water is decanted and the process repeated until the liquid decanted is clear. Thus obtained, the concentrate or powder is dried in the usual way and then submitted to a bromoform separation to isolate the " heavier " constituents. If the authigenous material is such as to mask the character of the fragments, clarification by means of dilute acid is carried out as previously described.

Recently much intensive research has been carried out and is in progress on the accessory minerals of granitic and associated rocks, with important results bearing both on their genesis and on their influence as contributors to sedimentary formations. This work follows particularly the lead of A. Brammall and H. F. Harwood in their exhaustive study of the Dartmoor Granite, to which reference is made ultimately. The technique implied follows closely that outlined in the preceding paragraphs on crushed rocks, and consists in pounding up several lumps of the rock, panning off the light powdery material (" flour ") produced, except in quantitative work (see above), thus gradually reducing the bulk until it is of reasonable size for bromoform concentration in the usual way. Thereafter various methods are employed for the isolation of particular mineral species (as described in previous pages), and these minerals are then accorded detailed individual study, both for their own sake and also for the evi-

dence they furnish of geochemical conditions attending the conception and consolidation of the granite. Further reference to this work and to its significance in sedimentary petrological studies, will be found on page 407, also in the Bibliography (p. 487).

Diagnosis of Detrital Minerals by Refractive Index (Immersion) Methods. Attention must now be directed to the method of precise refractive determination as a basis of identification of mineral grains and fragments. The practice has come into prominence considerably during the last few years, partly due to its popularity with American petrographers, and partly to the impetus accorded it by Larsen's work.¹ The method is invaluable for confirmatory diagnosis of individual mineral particles, but it is obviously unsuited as a means of determining and comparing composite assemblages of heavy minerals for correlation purposes, though this has actually been suggested in some quarters. As Prof. W. A. Tarr has said,² "the predominating factor in the study of sediments in Europe is the use of the microscope"; the tendency in this country is undoubtedly to rely on microscopic analysis, reserving special optical, microchemical or spectroscopical tests for doubtful individual cases. On the other hand, these immersion methods might be employed with advantage far more than they are at present, as in doubtful diagnosis they certainly help to narrow down possibilities accurately and speedily.

The determinations are most conveniently made by immersing the given grains in a drop of

¹ E. S. Larsen, "The Microscopic Determination of Non-Opaque Minerals," *U.S.G.S., Bull. No. 679*, 1921.

² W. A. Tarr, "Studies of Sediments in European Laboratories," *National Research Council, Researches in Sedimentation in 1924, 1925*, P. 35.

the selected liquid on a glass slip and observing their relative relief under the microscope; the application of the Becke Test (p. 87) will indicate whether the mineral possesses a higher or lower refractive index than that of the fluid in which it is immersed. When the refractive index of the mineral and of the medium are in accord, the former appears practically invisible. A glass slip with bowl-shaped hollow, similar to that recommended for mounting coarse material (p. 45) is a convenient form of mount for this purpose. Full details of other methods of employing refractive index liquids and of determining relevant values will be found in Larsen's work and in references there cited.

Different authors have proposed various liquids as immersion media according to their requirements and taste. It is possible, of course, to establish a very large range of liquids with refractive indices differing by small increments; for those engaged on very close and detailed work, an extended list is given below; generally speaking, however, those liquids marked with an asterisk (*) will suffice for ordinary work; these have the advantage of chemical stability, and, if carefully looked after, will last indefinitely; they are essentially the liquids adaptable for use under field-conditions, and are accordingly recommended.

REFRACTIVE INDEX LIQUIDS.

1.333	*Water ¹	1.444	*Chloroform
1.357	*Acetone	1.448	Kerosene
1.362	Ethyl Alcohol ²	1.448	Methyl Acetate
1.381	Ethyl Butyrate	1.450	*Petroleum
1.386	Methyl Butyrate	1.450	Ethylene Chloride
1.393	Ethyl Valerate	1.460	Lavender Oil
1.407	*Paraldehyde	1.463	Carbon Tetra- chloride
1.409	Amyl Alcohol ³	1.469	Olive Oil
1.425	Ethyl Bromide		

1.470	Russian Alboline	1.586	Aniline
1.472	*Turpentine	1.589	Bromoform
1.474	Liquid Paraffin	1.600	*Cassia Oil
1.477	American Alboline	1.615	Cinnamic Aldehyde
1.478	Almond Oil	1.628	*Carbon Bisulphide
1.481	*Castor Oil	1.635	α -Monochloronaphthalene
1.496	Toluol	1.655	α -Monobromnaphthalene
1.498	Benzol	1.700	*Cadmium Borotungstate
1.500	*Xylol	1.716	Potassium Mercuric Iodide
1.502	Valvolene ⁴	1.737-1.741	*Methylene Iodide ⁶
1.507	Sandalwood Oil	1.778	*Methylene Iodide Sulphur Soln.
1.516	Cedarwood Oil	1.868	Methylene Iodide, Sulphur and Iodides ⁷
1.516	Ethyl Iodide	1.68-2.10	Piperine and Iodides ⁸
1.525	Ethyl Salicylate	1.998Na-2.716Li	Sulphur and Selenium ⁹
1.526	Monochlorbenzol	2.72-3.17Li	Selenium and Arsenic Selenide ¹⁰
1.531	*Clove Oil ⁵		
1.535	Cinnamon Oil		
1.536	Ethylene Bromide		
1.539	Methyl Salicylate		
1.546	*Nitrotoluene		
1.548	Aniseed Oil		
1.550	Bromtoluene		
1.555	*Nitrobenzol		
1.558	Dimethyl Aniline		
1.561	Monobrombenzol		
1.570	Benzyl Benzoate		
1.572	Orthotoluidene		

Notes.

¹, ², ³ Solvent action on certain minerals of low R.I.

⁴ Any clean lubricating (mineral) oil may be used; will not mix with clove oil.

⁵ R.I. varies from 1.530 to 1.544; will mix with petroleum.

⁶ Place copper or tin in bottle to prevent discolouration (Larsen).

⁷ H. E. Merwin, *Wash. Acad. Sci. Journ.*, vol. iii., 1913, pp. 35-40.

⁸ H. E. Merwin, *loc. cit.* This and the next two compounds are solid at ordinary temperatures; used in a state of fusion. For preparation, see Larsen, *op. cit.*, and references cited.

⁹ H. E. Merwin and E. S. Larsen, *Amer. Journ. Sci.*, 4th Series, vol. xxxiv., 1912, pp. 42-47.

¹⁰ E. S. Larsen, *op. cit.*, p. 20.

N.B.—Solutions of intermediate R.I. can, if required, be obtained by mixing "limiting" fluids together and testing the product with an Abbé or Tully Refractometer, or with mineral fragments of known R.I.

The best method of storing these liquids is to keep them in "dropping bottles" supplied with a glass rod fused into the stopper. The bottles are kept in receptacles made by boring holes of suitable size in thick wooden blocks, each block containing ten or twelve bottles, on the principle suggested and illustrated by Larsen. *Use coloured glass bottles and keep the liquids in the dark when not in use.*

CHAPTER IV.

MICROSCOPICAL EXAMINATION OF SEDIMENTS.

The Petrological Microscope — Stereoscopic Binocular Petrological Microscope — Systematic Examination of Detrital Sediments under the Microscope — Refractive Index—Thickness of Grains—Isotropism—Birefringence—Interference Figures—Determination of Sign — Summary of the Optical Properties of Detrital Minerals —Difficulties in Identification of Detrital Mineral Aggregates—Rock-Fragments — Composite Aggregates —Use of Coloured Light in Diagnosis—Minerals Masked by Alteration Products.

The Petrological Microscope. Opinions probably differ more on the subject of the most suitable microscope for petrographic work than on any other piece of apparatus designed to aid analysis of rocks and minerals. For this reason no useful purpose would be served here in recommending any particular instrument for the work discussed in this volume. On the other hand, whatever instrument is chosen, it should at least embody the following as its essential equipment, which the author has found indispensable to his own work :—

“(1) A cross-webbed *Ocular* with adjustable eye-lens. If the analyser is mounted over the eye-piece, a slot should be cut in the ocular tube at 45° to the cross-wires to take a quartz-wedge, etc.

(2) A *Bertrand lens*. Some instruments are fitted with two, one to focus and another on a plate

which is also recessed to accommodate a *Klein Quartz Plate*.

(3) An *Analyser*, preferably sliding in and out of the body-tube, or it may be mounted over the ocular.

(4) A *Slot* with dust-proof cover, but at 45° to the cross-wires in the ocular below the analyser in the body-tube.

(5) A *Centring Nosepiece* (double or triple) to accommodate objectives.

(6) *Objectives*. A $1''$ and $\frac{1}{4}''$ or $\frac{2}{3}''$ and $\frac{1}{6}''$ are recommended for this work. Other objectives are available: see manufacturers' catalogues.

(7) A *Rotating Stage* divided into 360° reading by vernier to $5'$.

(8) A *Convergent System* (sub-stage condenser) mounted in an *Iris Diaphragm*, attached so that it can be swung in and out of the optic axis of the instrument.

(9) A *Polariser* so mounted that it can be swung in and out of the optic axis of the instrument, and fitted with spring catch to indicate zero position.

(10) A double *Mirror*, one side concave for convergent light, etc.

(11) *Fine Adjustment* (*Micrometer Screw*) with milled head divided to read to 0.01 mm. Sometimes a differential screw to read to 0.001 mm. is preferred."¹

Fig. 8 illustrates one such microscope with its components labelled, so that the novice should have no difficulty in appreciating the functions and positions of the vital parts concerned. It is of the utmost importance that before any serious work is begun, the microscope should be thoroughly

¹ C. Raeburn and H. B. Milner, "*Alluvial Prospecting*," 1927, p. 255.

understood, its potentialities mastered, and every adjustment familiarized; this statement may

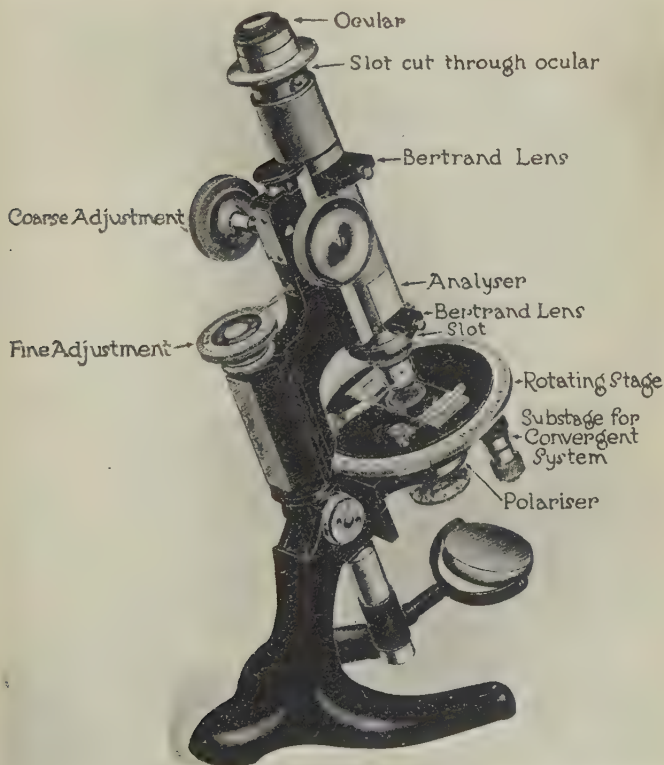


FIG 8. Petrological Microscope.

appear elementary, but it is remarkable how many difficulties in diagnosis or in optical determina-

tions, imagined by students, can be explained by their inability to use their instrument to the full extent of its powers. In cases where personal instruction is not immediately available, manufacturers' catalogues usually convey very full information on any particular model, while such books as C. Beck's "*The Microscope*" and his more advanced volume "*The Microscope, Part II*" will be found of value.

The petrological microscope will be found to fulfil all the functions demanded of it in normal petrographic work, *i.e.*, magnification, physical and optical measurements; this suffices for ordinary investigations, but where a great deal of microscopy is contemplated, especially concerning large rock-fragments, accessory minerals and micro-organisms in subsurface oilfield developments, the supplementary binocular microscope is invaluable.

The Stereoscopic Binocular Petrological Microscope. This type of microscope has come greatly into favour during the last few years with those engaged on petrographic and especially micro-palæontological researches. There had long been a demand for an instrument combining the advantages of stereoscopic relief with polarised light, a demand indirectly accentuated by the eye-fatigue occasioned by constant examination of many hundreds of slides, the lot of those concerned with such intensive work where the ordinary monocular pattern is in use. In this connexion, some remarks by M. I. Goldman on "Testing and Adjusting the Binocular Microscope," etc., are particularly apposite.¹

¹ *Bull. Amer. Assoc. Pet. Geol.*, vol. ix., p. 175.

In the accompanying illustration (*fig. 9*) a new British pattern of Stereoscopic Binocular

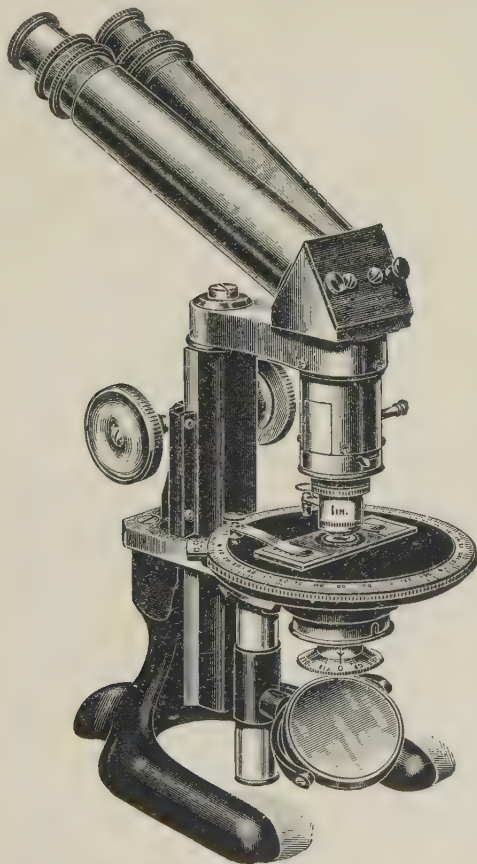


FIG. 9. Stereoscopic Binocular Petrological Microscope.

Petrological Microscope is shown, the chief features of the instrument being the range of objec-

tives possible (3in. — $\frac{1}{2}\text{in.}$, $\frac{1}{3}\text{in.}$, or $\frac{1}{4}\text{in.}$ if in short mounts), the adjustability of the draw-tubes containing the oculars to the correct inter-ocular distance of the observer, and a special low power achromatic condenser designed for micro-palæontological work, having a long working distance and yielding good dark ground illumination. The author has used such an instrument with much success with sands, heavy residues, dry air mounts of *foraminifera*, also mineral flakes immersed in refractive index media, etc. It is an unquestioned advantage where continued investigation of a long series of microscope slides is entailed.

As this instrument may take more understanding than the monocular pattern, the following notes may help the student in its use:—

(a) In the investigation of well-samples, large fragments of rock, fossils, individual minerals and all opaque materials, dark ground illumination is essential and may be secured by placing either a white or black card (depending on the colour of the substance examined) on the stage, and employing strong incident light.

(b) Everything depends on the correct adjustment and intensity of illumination, whether transmitted or incident, a matter of much greater importance than with the simple pattern microscope. If the daylight available is not sufficiently strong, use a 100 watt gas-filled "daylight" type electric lamp. With transmitted light, the rays should fall directly on to the concave mirror, care being taken to adjust so that the filament is not reflected in the instrument. With incident light, allow the rays to fall obliquely on to the object on the stage, unless special dark-ground illumination apparatus is employed, when this adjustment will be automatically made.

(c) The $1''$ objective normally suffices for all ordinary work with incident light with this instrument, but the higher power ($\frac{1}{4}''$) can be used when the object is not too large, care being taken not to scratch the objective when racking down to focus. For examination of thin sections, transparent objects, detrital mineral grains mounted on

glass slips, etc., with transmitted white light and 1" objective, the condenser is not required, and the polariser should be swung out of the optic axis until it is required for polarised light determinations. *Where the high power objective is being used with transmitted light, it is essential to employ the condenser, otherwise the illumination will not be sufficiently strong, or may be partially cut off.*

(d) Focussing is in all cases effected by the coarse adjustment, actually quite a sensitive mechanism, also to some extent by the oculars independently.

(e) For interference figures in rock-minerals with this instrument, insert the condenser, swing in the polariser, use the high power objective, push in the analyser, and remove both oculars: observation through either ocular-tube with the eye a little distance away from the aperture and, if necessary, shifted slightly to the right or left, will reveal the desired figure on a small scale. Determination of sign with a quartz-wedge is carried out in the normal manner by inserting it in the slot at the bottom of the body-tube underneath the analyser; the wedge is thus placed at 45° to the cross-wires; see page 92 *et seq.*

(f) Should there be any trouble with the nicol prisms owing to excessive heat of the tropics, detach both polariser and analyser and send them back to the manufacturers. This possibility is very remote indeed and can be largely avoided by keeping and using the instrument, or any microscope for that matter, in a cool room during this time. *(On no account attempt to repair the prisms without expert advice.)*

Systematic Examination of Detrital Sediments under the Microscope. A systematic investigation of detrital minerals is strongly recommended, until by experience the student has become proficient in the art of recognizing and discriminating between associated species. The plan of procedure may be summarized as follows:—

1. *With transmitted white light, low and high power objectives.*

- (a) Colour. Transparency, translucency or opacity.
- (b) Habit. Presence or absence of crystal faces.
- (c) Shape. Regular or irregular.
- (d) Size. Estimate or measure, if necessary, with eyepiece or stage micrometer.
- (e) Fracture. Uneven, conchoidal, etc.

- (f) Parting. Linear or irregular.
- (g) Cleavage. Principal and subordinate directions.
- (h) Abrasion, Degree of. Angularity, subangularity, roundness.
- (i) Refractive Index. Compare with Canada balsam (1.55).
- (j) Thickness of Grains.
- 2. *With reflected light against dark background to slide.*
 - (a) Lustre. Adamantine, metallic, submetallic, vitreous, resinous, etc.
- 3. *With transmitted light, polariser inserted.*
 - (a) Pleochroism. Presence or absence.
Weak or strong. Colour change with orientation of grain.
- 4. *With transmitted light, crossed nicols.*
 - (a) Isotropism or anisotropism.
 - (b) Birefringence (Interference or Polarisation Colours).
 - (c) Extinction. Straight, or oblique; in latter case determine angle.
 - (d) Order of Interference Colour (with quartz-wedge or other device).
 - (e) Vibration Directions; Relative Retardation (with quartz-wedge, gypsum plate, etc.).
- 5. *With convergent light, high power objective, crossed nicols and Bertrand lens.*
 - (a) Detection of interference figure: uniaxial or biaxial.
 - (b) Determination of the sign of the crystal by means of a quartz-wedge, gypsum or mica plate.
 - (c) Optic axial angle, dispersion, etc.

NOTES.

1. Most of these determinations are straightforward. Translucent minerals can frequently be rendered more transparent by inserting the condenser; similarly opaque minerals may be rendered slightly translucent on thin edges, *e.g.*, sphalerite, chromite. Cleavage may be an important diagnostic property, especially in thin sections, *e.g.*, amphiboles and pyroxenes, where two sets of cleavage lines may intersect at given angles. Many detrital minerals tend to exhibit conspicuous cleavage, *e.g.*, kyanite, topaz, calcite, fluorite. Degree of abrasion, *i.e.*, shape of grains, is an important factor in the study of heavy mineral residues for correlation (p. 389).

Refractive Index. The most common method of determining relative refractive index is that known as Becke's White Line Method. The test is as follows:—raise the objective and the white line (boundary of grain) travels from the substance of *lower* R.I. to that possessing the higher R.I. Fig. 10 makes this test clear. Another method is that of Oblique Illumination, or Schroeder Van der Kolk's Method. This requires some degree of skill to effect successfully: reference should be made to the works cited.¹

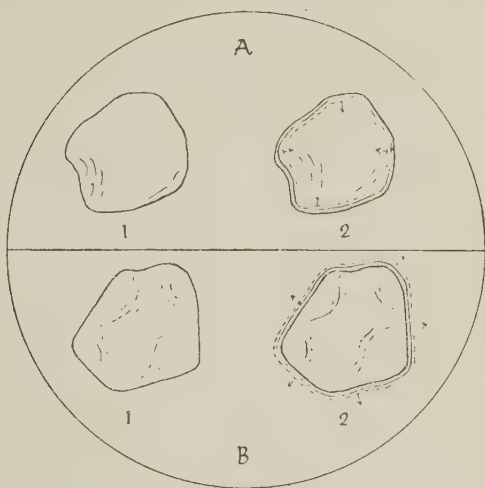


FIG. 10. Diagram to illustrate Becke's Line R.I. Test.

Medium: Canada balsam.

- A. 1. Topaz grain in correct focus.
- 2. Same with objective raised: margin travels inwards.
- B. 1. Fluorite grain in correct focus.
- 2. Same with objective raised: margin travels outwards.

Thickness of Grains. This measurement is carried out on unmounted material. "Make a mark on a glass slip with a diamond, and focus the mark with the micro-

¹ C. Raeburn & H. B. Milner, "*Alluvial Prospecting*," 1927, p. 275; also E. S. Larsen, *op. cit.*

scope. Place the grain over the mark and focus its upper surface (turn micrometer screw in same direction throughout). The difference in readings gives the thickness required. Another method is to focus the surface of the grain placed over a mark, then focus the mark through the grain. If the refractive index of the mineral is known, $T = nt$, where T = actual thickness, n = refractive index and t = measurement or difference in the two readings of the micrometer screw."¹ (See also Polarisation Colour Scale by W. R. Jones and A. Brammall referred to below).

2. For observations with dark-ground illumination, refer to paragraphs (a), (b) and (c) on page 84.

3. Direction of maximum absorption should be carefully determined, also whether fast or slow: see below, § 4. Pleochroism is best seen by rotating the nicol rather than the stage. The use of the high power objective and convergent light is extremely helpful where the phenomenon is only weakly displayed. Note the diagnostic value of "twinkling" in connexion with the rhombohedral carbonates (observed by rotating the polariser only). Pleochroic haloes are best investigated with high power objective and the convergent system.

4. *Isotropism*. The real test of isotropism is to try for an interference figure. Remember that basal sections of certain minerals will appear isotropic between crossed nicols, but may still give interference figures, hence such minerals are *not* cubic; e.g., anatase, tourmaline, quartz. Cubic minerals *in the absence of strain phenomena* are definitely isotropic and cannot possibly yield interference figures. (See optical summary on page 97.)

Birefringence. This is particularly important in thin sections and should be correctly determined, where possible accurately. W. R. Jones and A. Brammall have devised a useful adaptation of the Polarisation Colour Scale, whereby thickness of a mineral section or grain and its birefringence are used to determine its identity. Birefringence is equal to the Interference Colour Value divided by 1,000 times the thickness (in microns). This colour scale is not only reproduced on a card in handy form, but a very neat method is adopted for checking the colour and the order to which it belongs.²

¹ C. Raeburn & H. B. Milner, *op. cit.*, p. 259 and A. Holmes, "*Petrographic Methods*," p. 116.

² Published by J. Swift & Son, Ltd., 81, Tottenham Court Road, London, W.1.

Order of Interference Colour. This can also be determined by means of a quartz-wedge superimposed on a mineral grain, the latter so arranged that on inserting the wedge, the interference tint of the mineral is lowered in its order until compensation occurs, *i.e.*, grey or black (isotropism). The succession of colours traversed till the black band appears is a measure of the order of the original interference colour of the grain. In a similar way, if the wedge is suitably calibrated, the *Relative Retardation* in $\mu\mu$ of a section or grain may be determined.

Vibration Directions. The determination of the slow and fast vibration directions of a mineral, especially the character of maximum absorption in pleochroic minerals, is an important diagnostic feature. Orientate the mineral at 45° to its extinction position. Use a quartz-wedge¹ (*e.g.*, length slow ϵ) and insert in the usual slot. The interference colour is either raised or lowered in order: if raised, the slow direction of the wedge ϵ coincides with the slow direction of the mineral; if lowered, the slow direction of the wedge is parallel to the fast direction of the mineral.

5. *Interference Figure (Directions Image).* To obtain an interference figure with the ordinary petrological microscope, use the high power objective, convergent system, crossed nicols and Bertrand lens, with really good illumination; a much clearer figure with detrital grains is always procurable by removing the ocular and dispensing with the Bertrand lens. Sometimes the figure is better appreciated by holding the eye a little distance away from the body-tube aperture (ocular removed). It is a good rule to practise with specially cut mineral-sections which give complete figures, carrying out the necessary observations with quartz-wedge, gypsum or mica plate on known substances; this familiarizes the observer with the phenomena under the best conditions and serves to prepare his eye for less clearly defined figures, such as are often characteristic of detrital grains. *This optical property should be thoroughly mastered at the outset: it is an invaluable test in the diagnosis of detrital and all rock-forming minerals.* For interference figures obtainable with the binocular petrological microscope, see page 85.

The interference figure may be uniaxial (*fig. 11*)² or biaxial (*figs. 12, 13*). Complete uniaxial figures consist of

¹ N.B.—A gypsum or mica plate may be preferable in many cases, *e.g.*, with low relative retardation.

² FIGS. 11—18 are taken from "*Alluvial Prospecting*."

concentric coloured rings surmounted by a black cross which does not break up on complete rotation of the stage through 360° . In very thin sections or grains, the coloured rings may be replaced by a grey-blue background. Biaxial figures assume different complexions according to orientation; in the 90° position (*fig. 12*) the two "isogyres" unite to form a kind of black cross surmounting coloured lemniscates, similarly for the 0° , 180° and 270° positions. In the 45° , 135° , 225° and 315° positions the "cross" splits up into two curved isogyres opposing each other and convex inwards, surmounting coloured lemniscates as before. *Fig.*



FIG. 11. Uniaxial Interference Figure.

13 shows this. Both pseudo-biaxial and pseudo-uniaxial figures are sometimes displayed, in the former case a known uniaxial mineral exhibiting a black cross which just "parts" at the centre on rotation, *e.g.*, some varieties of quartz, and in the latter case a known biaxial mineral of exceedingly small optic axial angle only just shows the slight parting of the isogyres in the 45° position, *e.g.*, some varieties of biotite. A "compass-needle" figure, *i.e.*, one

isogyre rotating about a central point as the stage is turned, is yielded by the emergence in a crystal section of one optic axis (biaxial mineral), *e.g.*, basal plane of epidote.

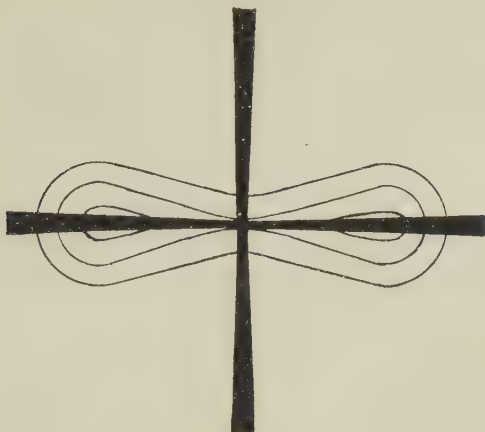


FIG. 12. Biaxial Interference Figure, 90° or Extinction Position.

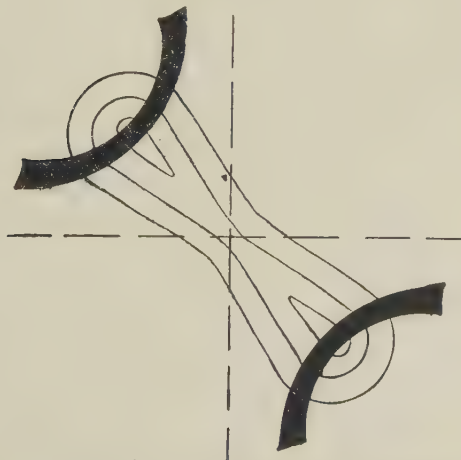


FIG. 13. Biaxial Interference Figure, 45° Position.

Determination of the Sign of a Mineral. Uniaxial Mineral. Two indices of refraction, ϵ and ω , corresponding to the extraordinary and ordinary rays respectively. ϵ vibrations are in the plane containing the optic axis, ω vibrations in a direction at right angles to this. If $\epsilon > \omega$ the mineral is *positive*; if $\omega > \epsilon$ the mineral is *negative*. Use a quartz-wedge (long direction ϵ slow),¹ and insert it in the slot of the body-tube of the microscope at 45° to the black cross. If the cross expands into two black spots in quadrants 2 and 4 (fig. 15) with corresponding ex-

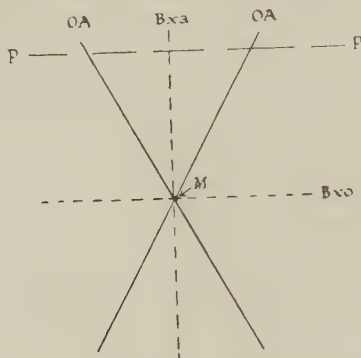


FIG. 14. Section through Optic Axial Plane, etc. OA, Optic axis; Bxa, Acute bisectrix; Bxo, Obtuse bisectrix; PP, relative orientation of crystal section which will exhibit a biaxial interference figure; M, Third Mean Line (Optic Normal) at right angles to plane of paper.

pansion of the rings in those quadrants, it will be found that the rings contract towards the centre in quadrants 1 and 3, *i.e.*, along the line of insertion of the wedge: the mineral is then *positive*. When the opposite movements take place, *i.e.*, expansion outwards in quadrants 1 and 3 (along the line of insertion of the wedge) and contraction inwards in quadrants 2 and 4, the mineral is *negative* (fig. 16). A good mnemonic for remembering this is that with a positive mineral an imaginary line joining the two black spots makes a *plus* sign with the length of the quartz-

¹ N.B.—Use gypsum plate if low order colour, or if black spots are obscure. Quartz-wedges are also cut with length fast ω ; in this case observations will be reversed.

wedge as inserted; if negative, the line coincides with the length of the wedge and a *minus* sign is suggested.

Biaxial Mineral. Biaxial minerals have three indices of refraction, α , β and γ ($\alpha < \beta < \gamma$), and, as the adjective im-

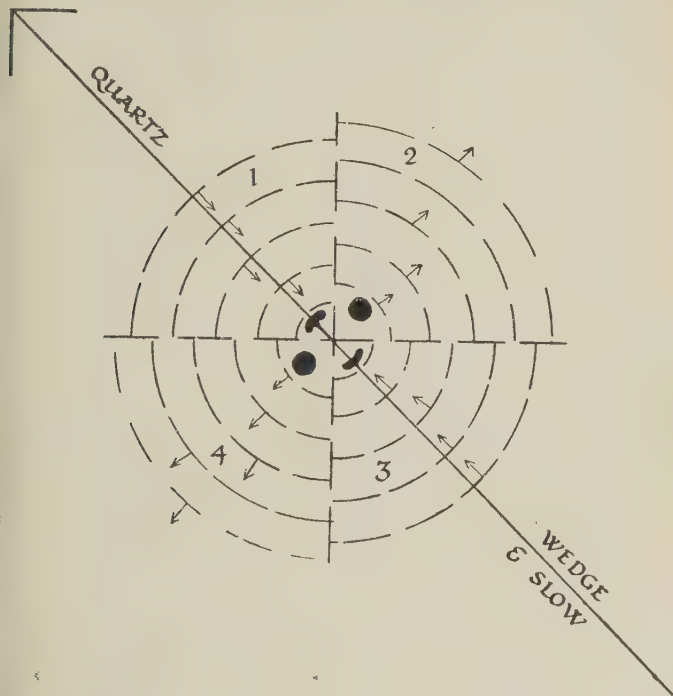


FIG. 15. Uniaxial Interference Figure: Action of Quartz-Wedge. Mineral POSITIVE.

plies, two optic axes, which are related as shown in fig. 14. If the bxa coincides with γ (Z), the mineral is said to be *positive*; if it coincides with α (X), the mineral is *negative*. To obtain the sign, orientate the figure in the 45° position and insert the wedge so that it coincides with the major

axis of the ellipse (this is provided for automatically in most makes of microscope by the position of the slot in the body-tube).

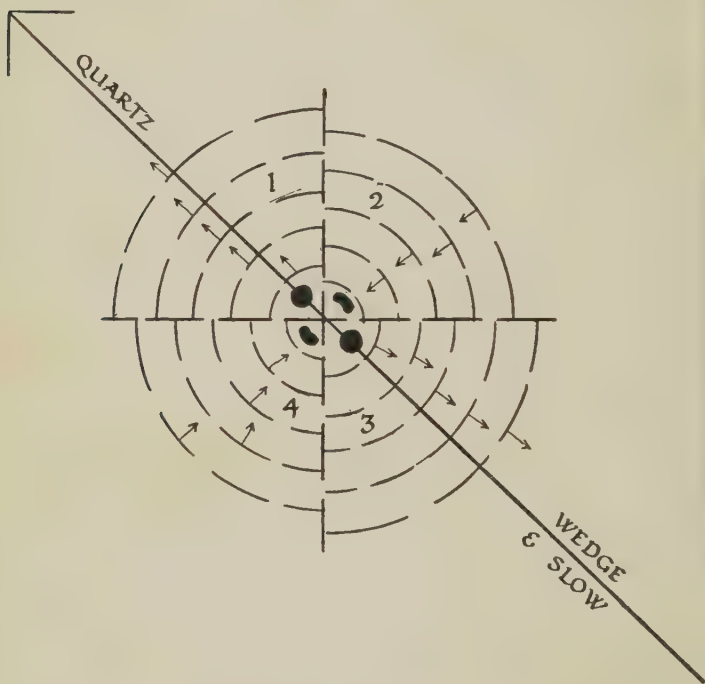


FIG. 16. Uniaxial Interference Figure: Action of Quartz-Wedge. Mineral *NEGATIVE*.

The mineral is *positive*: the isogyres appear to move towards each other along the line of insertion of the wedge, and the colour-bands move in the directions indicated in fig. 17. The mineral is *negative*: the isogyres appear to retreat outwards along the line of insertion of the wedge, i.e., "repel" each other, the colour-bands moving as in fig. 18. This method is however, somewhat empirical.

More accurately, determine the vibration-character (p. 89) of the plane exhibiting the biaxial figure (p—p, fig. 14): it is the trace of the bxo and if fast X, the bxa $\perp$ to the plane is Z, hence the mineral is *positive*. If p—p is slow, it is the trace of the bxo Z; thus the bxa = X and the mineral is *negative*. Interference figures $\perp$ bxo reverse these effects.

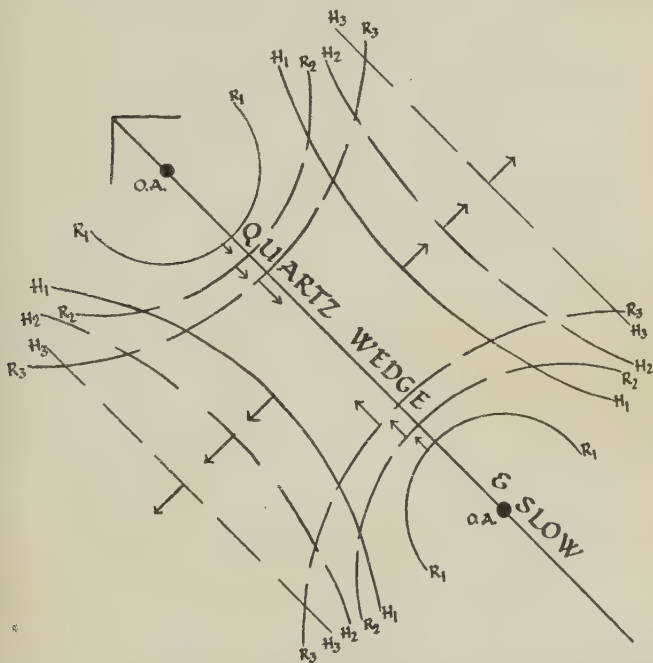


FIG. 17. Biaxial Positive Figure (Diagrammatic). As the quartz-wedge is inserted in the direction of the large arrow, so the rings R_1 move inwards towards each other, taking up successive positions R_2 , R_3 . Simultaneously the rings H_1 move outwards away from each other and take up position H_2 , H_3 . O.A. Optic Axes.

The chief difficulties in determination of interference figures are in cases where, owing to the crystal-section pre-

sented, only an incomplete or partial figure is exhibited. Eccentrically moving figures are often displayed. As a general guide, *though by no means infallible*, the following may aid interpretation:—when on clockwise rotation

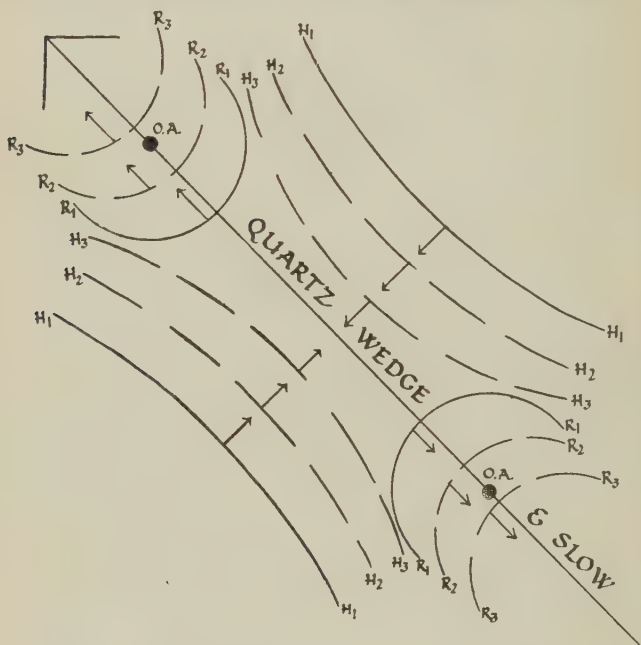


FIG. 18. Biaxial Negative Figure (Diagrammatic). As the quartz-wedge is inserted in the direction of the large arrow, the rings R_1 retreat outwards along the line of insertion, taking up the positions R_2 , R_3 . Simultaneously the rings H_1 move inwards towards each other, taking up the positions H_2 , H_3 . O.A. Optic Axes.

first a horizontal "arm," then a vertical "arm," then a horizontal "arm" and finally a vertical "arm" move successively into position, the whole moving rigidly without any curvilinear or sweeping movement across the field

of view, a uniaxial figure is suggested, even though only one or two such "arms" may be apparent. When an "arm" appears having a pendulum or compass-needle movement, it suggests a biaxial mineral, though sections markedly oblique to the optic axis of a uniaxial mineral also exhibit the former effect. It is seldom that, if some kind of image is displayed, something definite cannot be made of it, especially if full use be made of the quartz-wedge or gypsum plate and its influence on the colour-bands exhibited by the mineral be correctly assessed (p. 89). A sound knowledge of optical physics puts such matters beyond doubt, but it is not within the province of this book to go beyond the data given; and reference should be made to Winchell's "*Optical Mineralogy*" or Evans' "*Determination of Rocks and Minerals*," etc.

Similarly a working knowledge of crystallography is essential to the complete understanding, not only of the technique discussed above, but of the fundamental properties to be anticipated from minerals conforming to the principles on which that science is based. In this connexion, certain relationships between crystal systems and inherent optical properties may now be conveniently summarized.

SUMMARY OF THE OPTICAL PROPERTIES OF DETRITAL MINERALS.

1. *Amorphous (Non-crystalline).* Shapeless grains. No variation in directional properties. *Examples:—* Glauconite, Limonite.
2. *Cubic System.* Grains are singly refracting, isotropic and never pleochroic. *Examples:—* Fluorite, Garnet, Spinel. Under conditions of internal strain, some species may be anisotropic, *e.g.*, Garnet, Fluorite.
3. *Hexagonal System.* Grains are doubly refracting and sometimes pleochroic when coloured. Basal grains or those abraded transverse to the hexad-axis are isotropic, and yield uniaxial interference figures. Prismatic grains give straight extinction. *Example:—* Apatite.
4. *Rhombohedral System.* Grains are doubly refracting, and frequently pleochroic when coloured. Basal grains or those abraded at right angles to the principal axis are isotropic and yield uniaxial interference figures. Prismatic grains show straight extinction. *Examples:—* Calcite and Tourmaline.

5. *Tetragonal System.* Grains are doubly refracting and sometimes pleochroic when coloured. Basal grains or those abraded transverse to the principal axis are isotropic and yield uniaxial interference figures. Straight extinction for prismatic grains. *Examples* :—Anatase, Cassiterite, Rutile, Xenotime and Zircon.
6. *Orthorhombic System.* Grains are doubly refracting and often pleochroic when coloured. Never completely isotropic. Biaxial interference figures. Prismatic grains show straight extinction. *Examples* :—Andalusite, Brookite, Enstatite and Topaz.
7. *Monoclinic System.* Grains are doubly refracting, often pleochroic when coloured. Never isotropic. Biaxial interference figure. Straight or oblique extinction according to crystal plane to which surfaces examined are parallel. *Examples* :—Gypsum, Orthoclase, Epidote and Titanite.
8. *Triclinic System.* Grains are doubly refracting and usually pleochroic when coloured. Never isotropic. Biaxial interference figure. Grains usually give oblique extinction, but often fail to extinguish in any position. *Examples* :—Kyanite and Plagioclase Felspar.

[N.B.—Exceptionally for grains of biaxial minerals, the crystal-section examined under the microscope may be parallel to the circular section of the indicatrix. Such grains may show very low interference colours or almost isotropism].

Difficulties in the Identification of Detrital Mineral Aggregates under the Microscope. The petrography of sedimentary rocks is frequently complicated by an inherent difficulty of identifying certain rock-fragments, composite grains (compound minerals), iron- or carbon-stained flakes, green or white semi-opaque grains of "dirty" appearance, and a number of other possibilities well appreciated by those who spend much time in searching mineral concentrates under the microscope. The difficulty is accentuated by fineness of grade when, unless exceedingly good illumination and high power magnification are

employed, much of the concentrate may remain obscure. Even then, as Rastall has pointed out,¹ "it is notoriously difficult to apply the ordinary optical tests to very minute grains under a high power, even in the case of transparent minerals, and with opaque grains very little can be done." With a view to aiding diagnosis in such cases, the following hints from the author's experience may not be without some practical value.

ROCK-FRAGMENTS. Careful investigation of the coarser constituents of a sediment often reveals large fragments of miscellaneous sedimentary or igneous rocks which may be present as smaller particles in the main mass of the detritus; in this way a clue is obtained and certain types of rock-fragment anticipated. The commonly occurring types range from chert, quartzite, chalcedony, vein-quartz, pegmatite, slate, shale, "felsite," various igneous rocks, particularly the dark-coloured and usually somewhat altered basic hypabyssal and volcanic types, also mica-schist. As pebbles or large particles, these are not very difficult to determine, especially if cleansed of all cementing matter and examined with a strong lens. If, however, the coarse constituents reveal no counterpart of the fragments present in the finer mass, much can be done by observing the fragments in reflected light when the colour, form, surface-characters, lustre, etc., may suggest identity. Normally, unless the rock-fragments possess a high iron-content, they will be segregated by the bromoform-benzol solution or later by bromoform itself, in the process of routine separation previously described, so that they should not interfere greatly with the heavy mineral suite.

¹ R. H. Rastall, *Geol. Mag.*, 1x., 1923, p. 37.

COMPOSITE AGGREGATES (COMPOUND GRAINS). The attachment of iron-ore to quartz, mica to quartz, rutile to ilmenite, pyrite to chert, and such compound minerals as leucoxene, perthitic intergrowths of felspar, mica-chlorite-serpentine aggregates, shimmer aggregates, etc., are common occurrences in sediments, whose diagnosis may occasionally be troublesome. The compound *iron-ore-quartz* grain should betray its nature by its behaviour with polarised light, when the characteristic concentric interference colours of quartz are normally visible, and contrast with the opaque portion identified with reflected light. *Mica-quartz* grains are less common, but the two minerals can usually be differentiated by their slight difference of refractive index (mica having the higher value) tested by the Becke line method; the mica portion also will usually show a partial, if not a complete interference figure, while if the concentric coloured rings of quartz are discerned, this property will contrast with the pale grey-blue or grey-yellow colour of the mica; failing this, reflected light will reveal the vitreous lustre of the quartz and the pearly lustre of the mica, usually a sharp contrast. Compound *ilmenite-rutile* or *ilmenite-anatase* grains are generally straightforward to diagnose, the secondary crystals of the oxides being conspicuous by their colours, refractive indices and euhedrism. Cases have been noted, however, where the co-existence of the ilmenite-rutile aggregate can only be inferred by inspection of the grain by reflected light, when a reddish or crimson patch or border, contrasting with the steel-grey lustre of the unaltered ilmenite, is visible. This characteristic may, however, be noted with certain types of ilmenite in which there is no reason to suspect

decomposition and generation of rutile. *Chert* as a matrix or nucleus in composite grains is not uncommon, but should be readily identified by its aggregate polarisation; *pyrite* attached to it, may be fresh or altered to limonite, in either case recognized by reflected light; pyrite as a core is usually fresh and gives no trouble in identification. *Leucoxene* is a much debated substance, but one which is not difficult to label, owing to its characteristic appearance by incident light; according to Cathrein¹ this product is essentially titanite, sometimes accompanied by rutile; it has, however, a very different appearance from titanite and, in fact, shows every variation from the partially-altered ilmenite grain, through limonite or hæmatite-stained aggregates to the uniform white "unglazed porcelain" type of grain familiar to all workers. *Perthitic Intergrowths of Felspar* are identifiable, providing the grains are not clouded with kaolinitic or micaceous material, when the optical characters are discernible with polarised light; if microcline enters into the composition of such aggregates, the "partial" cross-hatching is always suggestive; if compounded of orthoclase and plagioclase, diagnosis is often difficult, especially with small grains. *Serpentine* aggregates with or without mica and/or chloritic matter, are common in certain types of sediment, especially those derived from basic and ultrabasic rocks. Such aggregates are not always easy to decipher, though the bright polarisation patches of serpentine contrast with the brilliant coloured mica flakes and the grey or "ultra blue" of chlorite, if these components are individually distinctive; often the aggregate may be a complex product resulting

¹ A. Cathrein, *Zeitschr. Kryst. Min.*, vol. vi., 1882, p. 244.

from the decomposition of some aluminous silicate, when the components lose their individuality as definite minerals and reveal themselves in the form of bluish-yellow birefringent grains possessing no particular extinction direction or other property aiding diagnosis; such grains frequently have a curious rough matted surface by reflected light, and this feature is sometimes helpful. *Shimmer-Aggregates* result from the decomposition of aluminous silicates, and usually consist of felted, cryptocrystalline, white micaceous material often crowded with inclusions. These interesting grains are very variable in form and optical character, often possessing no particular directional properties. The interference colours are normally high. By reflected light the felted structure is accentuated, and the lustre is that of a semi-vitreous or porcellanous character. G. Barrow has described aggregates of this type with cores of staurolite;¹ H. H. Thomas also records their occurrence in the Bunter Pebble Beds of the West of England.² *Pinite* is another aggregate, sometimes mineralogically distinctive, but generally of a micro- to cryptocrystalline character, rather micaceous, green in colour, and intimately associated with iron-ore; it usually results from the decomposition of cordierite. *Hæmatite*, either as an isolated mineral or as part of a composite grain, is seldom difficult of recognition on account of its characteristic red colour. If there is any doubt, however, the interposition of a green glass between the source of light and the aggregate (against a grey background), or the use of a green electric lamp, may prove useful; in these circumstances the hæmatite appears dull black.

¹ G. Barrow, *Q.J.G.S.*, vol. xlix., 1893, p. 349 & pl. xvi., fig. 5.

² H. H. Thomas, *Q.J.G.S.*, vol. lviii., 1902, p. 627.

Coloured light as an aid to petrographical work is not perhaps as freely invoked as it might be, either for transmitted or incident light observations. In practically all the instances cited, coloured electric lamps of sufficient strength, or the employment of suitable screens made of different coloured glass, may sometimes prove advantageous. The following colours have been successfully employed by the author in this connexion :—

Red for chlorite, glauconite, epidote, green mica aggregates.

Green for hæmatite.

Blue for limonite (especially limonitic patches on glauconite).

Yellow for any aggregate in which either purple ilmenite or pyrolusite is anticipated.

The effect in each case is to make the particular mineral components appear nearly black or quite dull, thus contrasting better with the associated minerals, especially if the latter are transparent or light coloured; such illumination enables the form of the chlorite, hæmatite, etc., to be picked out more easily.

MINERALS MASKED BY ALTERATION PRODUCTS.

The determination of minerals possessing superficial decomposition products, unremoved by the usual methods of clarification, is a well-known difficulty in work with detrital sediments. The cerium oxide film on monazite, the opaque green-black dust observed as a coating to the commoner pyroxenes and epidote, the chloritic alterations of the ferro-magnesian minerals, the carbonaceous matter associated with andalusite, the various masks assumed by the carbonate minerals: all these are common examples of destabilisation

products which serve to hide the true character of the original mineral. Sometimes the product may be diagnosed after careful inspection by incident light, whence the fundamental mineral or existing nucleus may be inferred. The use of the high power objective with convergent light frequently affords sufficient transparency for such deductions to be made with some accuracy; even optical determinations may be possible in these circumstances. On the other hand, the decomposition film is often so thick and comprehensive, that the microscope is powerless to resolve it, let alone the primary mineral concerned, in which case experience and intuitive deduction will be the safest guide. In point of fact, it is with these alteration products as with individual detrital grains: often the experienced investigator can be reasonably certain of his diagnosis without being very clear why his conclusions should impress themselves so decidedly on his mind. Perhaps this is one of the psychological peculiarities of this branch of petrographic work, but it is none the less a generally admitted fact.

Against all this, and purely as a temporary expedient when comparing mineral assemblages, the labelling of an unknown species as "X," while technically indefensible, may suffice until such time as more extended facilities are at hand for a thorough investigation. The recognition of "X" in a series of samples, providing it has constant mineralogical characteristics, may be of definite correlative value. While the author in no sense upholds this "make-shift" practice, it behoves him to mention at least one way of overcoming a difficulty so that the work of correlation may proceed without serious interruption arising from ignorance of specific identity.

CHAPTER V.

QUANTITATIVE DATA.

Acid Solubility—Birefringence—Bitumen: Estimation of Mineral Matter—Cohesiveness Test of Sands—Density—Frequency Factor—Grain Size—Heavy Mineral, Percentage of—Mechanical Analysis—Micrometric Analysis—Porosity—Ratio of Absorption—Saturation (Oil in Sands, etc.)—Shape of Pebbles, Rounding of Grains, etc.—Specific Gravity—Spherulitic Structure—Textural Analysis.

There is apparent among contemporary workers on sediments all over the world a laudable tendency to introduce more freely the quantitative element into petrographic work, which, after all, is as it should be. In certain directions, however, having regard to the nature of the materials studied, the tendency has been somewhat overdone; it is not always possible to reduce sediments to mathematical formulæ; neither is it desirable, even if it can be done. On the other hand, in view of this trend of thought, founded without doubt on the natural scientific aim at being precise rather than merely general in description, it is considered that some paragraphs dealing with this particular aspect of the subject should now find a place in this work. At the outset, the author disclaims any intention of expanding this volume into a full treatise on petrographic methods, or of an attempt to interpret the term "sedimentary petrography" in any wider sense than it has come to mean at the

hands of modern workers. The data here put forward are purposely brief and void of experimental detail; they are intended (1) to act as a summary, (2) to serve as an indication of the evaluations now commonly made in the study of sedimentary rocks, and (3), most important of all, to inspire reference to those books and papers cited, which far more ably and in greater detail treat of these matters.

For convenience the data are arranged alphabetically.

Acid Solubility. That quantity of a sediment soluble in hydrochloric acid. Implies organic rocks, but not exclusively. Useful factor for comparing samples of calcareous rocks from different horizons or localities, also for expressing their purity or impurity (contamination by detrital and/or authigenic constituents). The specimen is pulverized, the powder being added slowly to cold acid in a beaker; stir constantly; warm if necessary; continue digestion till all effervescence ceases. $A = \frac{100(w - w_1)}{w}$

where A = percentage solubility of rock, w = initial weight of crushed rock before treatment, w_1 = weight of residuum after digestion.

Birefringence. (a) Calculated from refractive indices. For uniaxial minerals $B = \epsilon - \omega$ or $B = \omega - \epsilon$, where ω = R.I. of ordinary ray, and ϵ = R.I. of extraordinary ray. When $\epsilon > \omega$ the birefringence is +, when $\omega > \epsilon$ birefringence is -. For biaxial minerals $B = \gamma - \alpha$ where α and γ = R.Is. ($\alpha < \beta < \gamma$). When γ (Z) coincides with the bxa the mineral is +; when α (X) coincides with the bxa the mineral is -. (See page 88 *et seq.*)

(b) Calculated from thickness of mineral. $B = \frac{I}{1000 \times T}$ where B = birefringence, I = interference colour value, T = thickness in microns. (See Polarisation Colour Scale by W. R. Jones and A. Brammall, ref. p. 88).

Bitumen: Estimation of Mineral Matter. Sample dissolved in carbon bisulphide, carbon tetrachloride or benzol in the proportion of 1 grm. to 100 cc. of solvent. Filter through Gooch crucible using asbestos mat, pressure flask and vacuum pump. Residual insoluble material is

washed with solvent, dried at 100° C, cooled, weighed, then ignited to eliminate other organic matter and reweighed. Percentage mineral matter given by 100 $\frac{[(W-w)-w']}{W}$

where W = weight of sample taken, w = weight of residual mass before ignition, w' = weight of residue after ignition. The reason for recording both w and w' is that, contrary to what is generally supposed, these bitumens frequently contain organic matter expelled by ignition but not soluble in organic solvents. (See also page 70).

Cohesiveness Test of Sands. For relative cohesiveness of different sands and as an indication of the amount of water which will develop the optimum of cohesiveness. (Equivalent to "bonding" tests in foundry practice). Simplest method is what is known as the "Bar Test" fully described by R. J. Doty, *Foundry*, Jan., 1923, and later by H. Ries and C. M. Nevin, *Trans. Amer. Found. Assoc.*, XXXI, 1924. It consists in ramming a known quantity of sand in a mould-box with a 20-lb. weight dropped between two guides from a height of 16 inches, six blows being given per test. The data required and obtained by this test include the weight of sample in grams, thickness of the bar in inches, average weight of break in grams, and recalculated weight of break to one inch thickness; the correction for water content necessitates knowing the percentage of water with which the sample is gauged and recalculating weight of break to a dry sand basis, on which all cohesiveness tests should be compared. (See also relevant papers in *Trans. Amer. Found. Assoc.*, XXXII, 1925).

Density. Applied to a rock-specimen, is the ratio of its mass to its volume, in other words, mass per unit volume. If density is expressed in C.G.S. units it is numerically equivalent to specific gravity (q.v.). In F.P.S. units, density is the mass in lbs. per cubic foot; 1 cub. ft. of water at 4° weighs 62.4 lbs., hence density divided by 62.4 will be equivalent to specific gravity in these units.

Elutriation. See under Mechanical Analysis, p. 108.

Frequency Factor. The relative proportions of specific minerals or varieties of those minerals occurring in a given heavy residue. There exist various methods of expressing such frequencies, chiefly qualitative and visual. The only satisfactory quantitative method is that of counting grains in slides under the microscope; accuracy depends as much on completeness of extraction of the total residue

from the sample as on actual counting, though it may not be necessary to utilize the whole residue for the count, a system of "proportioning," as with alluvial concentrates, being adopted. Results are expressed as percentages. For details and examples of procedure see W. F. Fleet, *Geol. Mag.*, lxiii., 1926, pp. 505-516, and also *Proc. Geol. Assoc.* XXXVIII, 1927, pp. 1-48. (cf. p. 383 of this volume for application of frequency values to correlation by petrographic methods.)

Grain-Size. The ratio of maximum grain area to mean grain area. With uniform grain-size this ratio is between 1.5 and 2 (variation of + or - 10% in volume from the mean is allowed). (See paper by G. H. Gulliver, *Journ. Inst. Metals*, XIX, 1918, p. 145; also A. Holmes, *Petrographic Methods*, 1921, p. 341).

Heavy Mineral, Percentage of. Express as percentage in terms of original sample: $\frac{100x}{w}$, where x=weight of

heavy mineral obtained after separation and w=weight of sample originally taken (always calculate on the natural rock, not on the acid-cleaned material). In some cases where bromoform of low gravity (2.75) is purposely used to segregate quartz from associated minerals, the percentage of heavy residue >2.9 (bromoform) calculated on the total residue >2.75 is used as a factor in correlation. The same formula applies, but in this case x=net amount of residue >2.9, and w=amount of residue >2.75. Known as the " $\% H.R.$ to Total $H.R.$ factor," an unnecessary refinement if standard bromoform is always employed.

Impregnation, Percentage. See under Bitumen; also p. 70.

Mechanical Analysis of Loose Sediments. For suitable apparatus see fig. 4, p. 57. British convention follows mainly the data given by Prof. P. G. H. Boswell in his memoir on British glass-sands (bibliography, p. 488). According to this, sedimentary rock-particles may be conveniently classified as follows:—

Classification of grades or "size-limits."

>2	mm. diam.				Gravel (G).
>1	mm.	„	& <2	mm. diam.	Very coarse sand (VCS).
>0.5	mm.	„	<1	mm.	Coarse sand (CS).

>0.25 mm.	„	„	<0.5 mm.	„	Medium sand (MS).
>0.1 mm.	„	„	<0.25 mm.	„	Fine sand (FS).
>0.05 mm.	„	„	<0.1 mm.	„	Superfine sand or coarse silt (s).
>0.01 mm.	„	„	<0.05 mm.	„	Silt (s).
<0.01 mm.	„				Clay or mud (c).

N.B.—1 mm. $\approx$ 0.04 ins., 0.1 mm. $\approx$ 0.004 ins., 0.01 mm. $\approx$ 0.0004 ins.

Velocities of water currents required for separating suitable grade-sizes (by means of elutriation) are:—

0.4 mm. diam.	47 mm. per second.
0.3 mm. „	32 mm. „
0.25 mm. „	25 mm. „
0.2 mm. „	20 mm. „
0.1 mm. „	6.7 mm. „
0.05 mm. „	1.78 mm. „
0.01 mm. „	0.12 mm. „
(Temperature 15° C.)	

Mechanical analyses are expressed either as “fractions” or graphically. In the former case an example shows:—

$$\frac{VCS}{11.8}, \frac{CS}{44.1}, \frac{MS}{41.5}, \frac{FS}{2.2}, \frac{s}{0.2}, \frac{c}{0.2}; \frac{S}{99.6}$$

where the letters denote the grades (as above), S = total sand-grade (>0.1 mm. diam.). In the latter case grade-sizes (in mm. diam.) are plotted against cumulative percentage weights. Grade-sizes are set off on the horizontal scale at intervals proportional to the logarithms of the diameters if the space allotted to the diagrams is limited. (See also A. Holmes, *Petrographic Methods*, 1921, p. 204 *et seq.*).

Elutriation for achieving the above results is now chiefly carried out by means of a single vessel elutriator, such as is illustrated in *fig. 4*, p. 57, also in the publications referred to, from which full information regarding this technique may be obtained.

American convention in mechanical analysis follows that used by C. K. Wentworth and others, in which the rudaceous constituents are also considered, as follows:—

256 mm. ...	Boulder.
64 mm. ...	Cobble.
4 mm. ...	Pebble.
2 mm. ...	Granule.
1 mm. ...	Very coarse sand grain.
$\frac{1}{2}$ mm. ...	Coarse sand grain.
$\frac{1}{4}$ mm. ...	Medium sand grain.
$\frac{1}{8}$ mm. ...	Fine sand grain.
$\frac{1}{16}$ mm. ...	Very fine sand grain.
$\frac{1}{256}$ mm. ...	Silt particle.
$\frac{1}{256}$ mm. ...	Clay particle.

In this scheme expression of mechanical composition is by means of "blocks" plotted on rectangular graph paper, diameters along the horizontal (decreasing values from left to right) and percentages along the vertical (increasing values upwards). The rectangles forming the framework of the "blocks" are twice as long (vertical) as broad (horizontal), usually of dimensions 8 mm. x 4 mm.

Further details are given by Wentworth in his paper on grade terms, etc., *Journ. Geol.*, vol. XXX, 1922, pp. 377-392.

For coarse sands, etc., and where elutriation is impracticable, sieving is resorted to for grading, but the results do not achieve a great degree of scientific accuracy. The sieves generally employed are detailed in the schedule on p. 37. The method of expressing results of sieving is very simple; *e.g.*, where 30-, 60- and 90-mesh sieves are used for a given sample, four separate grades (approximate size-limits) will be obtained and each weighed, from which, knowing the weight of the sample taken, percentage proportions can be calculated; the expression is as follows:—

Sand retained by 30-mesh sieve . . . + 30 w%.

Sand passed by 30- and retained by 60-mesh . . . —30 + 60
. . . x%.

Sand passed by 60- and retained by 90-mesh . . . —60 + 90
. . . y%.

Fines passed by 90-sieve, —90 . . . z%.

Approximate sieve (I.M.M.) equivalents to metric grade-sizes are :—

I.M.M.		METRIC GRADES.	
12	— 5 $\approx$	1.0 mm.	— 2.0 mm.
20	— 12 $\approx$	0.5 mm.	— 1.0 mm.
50	— 20 $\approx$	0.25 mm.	— 0.5 mm.
120	— 50 $\approx$	0.1 mm.	— 0.25 mm.
180	— 120 $\approx$	0.05 mm.	— 0.1 mm.

Micrometric Analysis. Delesse-Rosiwal Linear Method of estimating volume percentages for minerals occurring in rocks. A celluloid linear or co-ordinate pattern micrometer is employed (stage or eyepiece micrometer). Record the number of intercepts for each particular mineral, taking a series of different, parallel lines of interception by moving the slide or micrometer into successive positions; the total length measured must be from 100-200 times the average grain of the rock. The total number of intercepts recorded for each mineral is reduced to percentage of the sum of individual totals and thus an approximate volume percentage for each mineral established. (See A. Holmes, *Petrographic Methods*, 1921, p. 312 *et seq.*). Another method is the use of Shand's Recording Micrometer, a specially designed stage pattern, which obviates much of the tedious work of the former method. (See S. J. Shand, *Journ. Geol.*, xxiv., 1916, p. 394, also A. Holmes, *op. cit.*, p. 319).

Porosity. The ratio of pore-space to the volume of rock (including pore-space). See also *Ratio of Absorption*. Gross porosity is the percentage aggregate of pore-space within the rock, as distinguished from net porosity = percentage pore-space in communication, *i.e.*, a measure of permeability. The following formulæ will be found to cover most cases :—

$$P = \frac{D(W_s - W)}{W + D(W_s - W)} \times 100,$$
 where D = specific gravity of sand (or rock-substance), W_s = weight of water-saturated sand in air, W = weight of dry rock in air, and P = porosity. (A. Holmes, *op. cit.*, p. 47). King's formula, used in connexion with water percolation through soils, etc., is :—

$$\frac{Vd - W}{100 Vd} = P,$$
 where V = volume of glass pot used (in cc.), d = specific gravity of sand, and W = weight of sand in grms.

(U.S.G.S., 19th Ann. Rep., Pt. 2, p. 208). Percentage pore-space is also given by:—

$$\frac{W^1 - W^2}{D} \times 100$$
 where W^1 = weight of water to fill pot, W^2 = weight of sand, and D = specific gravity of sand, usually taken as 2.65. In the same way, since $W^2 = \text{volume of sand}$,

$$P = \frac{D}{V_p} \times 100$$
 where P = porosity, V_p = volume of pore-
 V_s

space, and V_s = volume of sand including pore-space. A much favoured American method is "Russell's Porosity Tube Method" using acetylene tetrachloride. (See *Bull. Amer. Assoc. Pet. Geol.*, x, 1926, p. 931. Apparatus made by Aimer and Amend, New York City).

Ratio of Absorption. Expressed as percentage, is the ratio of the volume of pore-space and the weight of dry rock multiplied by 100. Given by $\frac{W_s - W}{W} \times 100$ where

W_s = weight of water-saturated rock in air, W = weight of dry rock in air, and volume of pore-space = $W_s - W$. (See A. Holmes, *op. cit.*, p. 46).

Saturation (Oil in Sands, etc.) Melcher's Method. Sample first shaped so that surplus oil can be wiped off surface; it is then evacuated of air by placing in vacuum chamber and using a pump. Oil of same origin to that impregnating the sample is admitted to the chamber and made to cover sample. Pressure is raised to 100 atmospheres or, if practicable, to approximately the calculated pressure of the oil in the reservoir concerned, temperature being adjusted to that of reservoir conditions (*i.e.*, according to depth). After a few hours the sample attains constant weight, and the whole apparatus is weighed while the sample is still submerged in oil. Then the sample is removed from the vessel, oil is cleaned from the surface and sample weighed in air. Finally, sample is crushed, oil burnt off or dissolved in CS_2 and sample again weighed; the difference between this and the previous weight gives the weight of the oil absorbed. Calculations are made as follows:—Let W = weight of sample saturated with oil, W' = weight of sample saturated with oil and submerged in oil, W'' = weight of sample free from oil and

moisture, and D = specific gravity of oil at temperature of experiment, then the percentage by volume of the sample filled with oil is :—

$$S = \frac{W - W''}{\frac{W - W'}{D}} \times 100 = \frac{W - W''}{W - W'} \times 100.$$

(U.S. Bureau of Mines. Bull. 243, 1926, p. 130).

Shape of Pebbles, Rounding of Grains, etc. *Wentworth's formulæ* :—mean diameter is given approximately by $D = \sqrt[3]{D' D'' D'''}$, where D' , D'' and D''' are the length, breadth and thickness measured. Roundness ratio is given by $\frac{R}{D} = 2r_1$, where r_1 is the radius of curvature in

mm. of the sharpest edge, and R the mean radius of the pebble. Flatness ratio is given by $\frac{D' - D''}{D'''}$ or the average

of length and breadth divided by thickness, or it may be given by r_2 in which $r_2 = \frac{R}{D}$ "radius of curvature in the most

convex direction on the flattest developed face or portion of the surface." Radii are measured by contact method with a gauge similar to that used by opticians to measure curvature of lenses. Values of r_1/R and r_2/R for each pebble are plotted on double logarithmic chart, the former as ordinate, the latter as abscissa. (See C. K. Wentworth, U.S.G.S., Bull. 730, 1923, pp. 91-114, also *Prof. Paper* 131, 1923, pp. 75-83, and *Journ. Geol.*, vol. xxvii., 1919, pp. 507-522).

Mackie's formulæ :—Rounding of grains is directly proportional to total friction suffered and inversely proportional to hardness; friction is a function of weight, distance travelled by the grains and velocity of movement. For wind transport, $R \propto \frac{V \times \text{S.G.} \times D \times V_e}{H}$, where R =

total amount of rounding, V = volume, S.G. = specific gravity, D = distance, and V_e = velocity. For water transport, $r \propto \frac{V \times (\text{S.G.} - 1) \times d \times v_e}{H}$, where S.G. - 1 = loss

of weight due to water displaced. Thus the ratio of rounding for wind and water, for any mineral of particular grade, is given by $\frac{R}{r} = \frac{\text{S.G.} \times D \times V_e}{(\text{S.G.} - 1) \times d \times v_e}$.

will be noted that
$$R \propto \frac{L^3 \times \text{S.G.} \times d}{4L} \text{ or } R \propto \frac{L^2 \times \text{S.G.} \times d}{4h}$$

where L = the length of one side. (See W. Mackie, *Trans. Edin. Geol. Soc.*, vol. vii., 1897, p. 298, *et seq.*; A. Holmes, *op. cit.* p. 201; W. H. Twenhofel, *Treatise on Sedimentation*, 1926, p. 57). Degree of rounding, or angularity, are, among others, properties sought in "textural analysis": see below.

Specific Gravity. (a) *Hydrostatic Method.* Specimen weighed in air, then in distilled water. $\text{S.G.} = \frac{W}{W-w}$, where W = weight in air, w = weight in water. Correction for temperature given by $d = \frac{W}{W-w} \Delta t$, where d = density

or weight of unit volume, $W = vd$, where v = volume, $w = W - v\Delta t$, t = temperature of observation, Δt = density of water at t° . The method is applicable to consolidated rock-specimens.

(b) *Displacement Method*: applicable to consolidated and unconsolidated rocks. Use a flask with graduated neck; fill with distilled water to given volume-mark, v , then weigh, w . Specimen is then added, new volume noted v' and the whole reweighed, w' , whence $\text{S.G.} = \frac{W}{v' - v}$.

(c) *Jolly Spring Balance*: for small specimens. First reading of the bead-pointer is taken, a . Specimen then placed in upper pan and new reading taken, b . Specimen then transferred to lower pan in water, height of beaker adjusted and a third reading taken, c . $b - a \propto$ weight in air, and $b - c \propto$ to loss of weight in water. Hence $\text{S.G.} = \frac{b - a}{b - c}$.

(d) *Pycnometer Method*: for sands and incoherent materials. Fill the bottle to one third with sample and weigh, W . Add distilled water till all the air is expelled and reweigh, whence weight of water is w'' . Weight of water required to fill bottle is w' ; hence $\text{S.G.} = \frac{W}{w' - w''}$.

(e) *Sollas Diffusion Column*: (Methylene Iodide method), for isolated mineral fragments. Use a test-tube and pour in about 2 cc. methylene iodide and then (carefully) 10 cc. benzol. Allow tube to stand (corked) until diffusion has

taken place, usually about 24 hours. Take fragment of mineral M whose S.G. is required, and two fragments A and B whose known S.G.s are respectively $>$ and $<$ M, found by trial from selection of previously tested fragments. Some scale should be clamped behind the tube so that the distances BM and BA are comparable. Let $b = \text{S.G. of B}$, $a = \text{S.G. of A}$, and $m = \text{S.G. of M}$, then $\frac{a-m}{m-b} = \frac{AM}{BM}$; $\therefore$

$m = \frac{bAM + aBM}{AB}$. Other methods employ the *Walker Steel-*

Yard Balance (for large specimens) and the *Westphal Balance* (chiefly for liquids). (See Holmes, *op. cit.*, ch. II, for very full data of all the above specific gravity methods, also Miers, *Mineralogy*, 1902, pp. 189-193).

Spherulitic Structure. The study of the form of surface of contact between two interfering spherulites may throw light on the law of their growth. This matter has been discussed by Popoff, also by Harker. More recently Spencer has discussed the relevant mathematics in an appendix to his paper on spherulitic siderite. (See papers by Popoff in *Forh. Nord. Naturf. Helsingfors*, 1902, sect. iv, and *Tscherm. Min. Petr. Mitth.* (2), vol. xxiii., 1904, pp. 153-179; A. Harker, *Nat. Hist. Ig. Rocks*, 1909, pp. 272-280; E. Spencer, *Q.J.G.S.*, vol. lxxxi., 1925, p. 693 *et seq.*, also references on p. 692).

Textural Analysis. Concerns quantitative expressions of texture of sedimentary rocks in terms of grade-sizes and shapes of clastic constituents. Applied particularly to sands, sandstones, grits, conglomerates, breccias and the like. Grade-size is expressed conventionally as summarized under Mechanical Analysis, p. 108. Shape is expressed quantitatively by Wentworth's method (p. 113) or more usually qualitatively as *rounded*, *subangular* or *angular*. Other determinations under this heading are percentage grade-sizes present for all constituents independent of their gravity, percentage heavy mineral per grade-size, percentage of one or more characteristic shapes of constituents developed, also measurements of any particularly prominent structures observed in the rock under analysis.

CHAPTER VI.

DIAGNOSTIC PROPERTIES OF SEDIMENTARY ROCK MINERALS.

In this chapter is a summary of the principal properties of those mineral species likely to be met with in sedimentary rocks. Excluding purely alluvial minerals and those essentially the recent products of local environments, the lists will be found complete for all normal work, as far as present knowledge goes. Obviously, of a total of some eight thousand different minerals now known to science, a very large percentage is capable of occurring in sedimentary deposits given relevant parent-rocks in the region concerned; exhaustive treatment would thus demand a text-book of detrital mineralogy which many considerations render impracticable. Experience, however, shows that a comparatively small proportion of minerals are identifiable in sedimentary rocks *of any geological age*, and that it is only when recent, especially alluvial deposits are studied, that the list can be indefinitely expanded; even in the latter case, it is in some respects surprising how many species fail to survive, and a study of the records of alluvial minerals from all over the world soon reveals the restriction of species imposed by destructive chemical and mechanical forces.¹

The detailed information given in this chapter should in itself be sufficient for determining a par-

¹ C. Raeburn & H. B. Milner, *op. cit.*, ch. x., p. 324.

ticular mineral, but a working knowledge of crystallography—a *sine quâ non* to this particular study—is assumed throughout. As will be seen, the information is consistently arranged under stereotyped headings, *viz.*, chemical composition, system of crystallization, habit, structure, cleavage, fracture, hardness, specific gravity, lustre, colour, magnetic and electrostatic properties, optical properties, characters in sediments, occurrence, possible sources of derivation, remarks, and special references to recorded occurrences or to general literature. Few of these headings require explanation.

The essential crystallographical, physical and optical properties given have reference to both well crystallized original minerals and to their detrital (or authigenic) occurrences. The particular interpretation with which we are concerned, *i.e.*, the modifications undergone by minerals during their transference from parent-rock to sedimentary deposit, or, maybe, during their growth *in situ* in certain well-defined environments, is dealt with in the paragraphs "Characters in Sediments." Under this heading is included those peculiar properties by which sedimentary rock minerals have come to achieve individuality, by which, in fact, they are correctly diagnosed with the aid of the microscope. Detrital mineral variations are legion; only constant experience with them in all kinds of deposits from world-wide sources can bring real competence in their identification and interpretation. The data given represent the average results of the author's examination of a large and varied selection of examples in each case, reinforced, where appropriate, with references to special published observations of other petrographers.

The practice of making a selection of the principal occurrences of each mineral (first adopted in the "Supplement" to the original volume in 1926), has met with widespread approval in facilitating reference to good localities, to authors directly concerned with relevant descriptions, and in conveying an idea of geographical and chronological ranges, and is accordingly continued here. The occurrences are chiefly British and are arranged in stratigraphical (ascending) order. The corresponding literary references are indicated at the foot of each description.

In every case provenance is suggested ("Possible Sources of Derivation"), a matter of obvious importance in any comprehensive investigation of a sediment. Thus, likely parent-rocks are noted, the information aiding palæogeographical investigations, etc.

The following is the complete list of the minerals fully treated in this chapter :—

Actinolite	Chromite
Anatase	Cordierite
Andalusite	Corundum
Anhydrite	Diopside
Apatite	Dolomite
Aragonite	Dumortierite
Augite	Enstatite
Axinite	Epidote
Barite	Fluorite
Biotite	Galena
Brookite	Garnet
Calcite	Glauconite
Cassiterite	Glaucophane
Celestite	Graphite
Ceylonite	Gypsum
Chalcedony & Chert	Hæmatite
Chiastolite	Hornblende
Chlorite	Hypersthene
Chloritoid-Ottrelite	Ilmenite

Kaolinite	Quartz
Kyanite	Rutile
Limonite	Serpentine
Lepidolite	Siderite
Leucoxene	Sillimanite
Magnetite	Sphalerite
Marcasite	Spinel
Microcline	Spodumene
Monazite	Staurolite
Muscovite	Titanite
Olivine	Topaz
Orthoclase	Tourmaline
Picotite	Tremolite
Plagioclase	Vesuvianite
Pyrite	Xenotime
Pyrolusite	Zircon
Pyrrhotite	Zoisite & Clinozoisite

The following is a list of mineral varieties referred to under their appropriate headings in this chapter :—

Ægirine (Augite)*	Hiddenite (Spodumene)
Albite (Plagioclase)	Indicolite (Tourmaline)
Almandine (Garnet)	Kunzite (Spodumene)
Ankerite (Dolomite)	Labradorite (Plagioclase)
Andesine (Plagioclase)	Lepidolite (Biotite)
Andradite (Garnet)	Microperthite (Plagioclase)
Anorthite (Plagioclase)	Oligoclase (Plagioclase)
Anorthoclase (Microcline)	Penninite (Chlorite)
Antigorite (Serpentine)	Phlogopite (Biotite)
Arfvedsonite (Hornblende)	Pinite (Cordierite)
Asbestos (Tremolite)	Pyrope (Garnet)
Barkevicite (Hornblende)	Riebeckite (Hornblende)
Bastite (Enstatite)	Ruby (Corundum)
Bronzite (Enstatite)	Sapphire (Corundum)
Bytownite (Plagioclase)	Selenite (Gypsum)
Chrysotile (Serpentine)	Spessartite (Garnet)
Clinocllore (Chlorite)	Steatite† (Tremolite)
Cymatolite (Spodumene)	Thulite (Zoisite)
Diallage (Diopside)	Uvarovite (Garnet)
Flint (Chalcedony)	Viluite (Vesuvianite)
Grossularite (Garnet)	

* Refer to the minerals in brackets. † Alteration product.

At the end of this chapter (p. 260) brief descriptive notes will be found on the following essentially sporadic and local minerals, together with appropriate references to their records :—

Ægirine	Magnesite
Ænigmatite	Melanite
Agate	Opal & Hyalite
Basaltine	Orthite
Benitoite	Piedmontite
Collophane	Phosphorite
Crossite	Psilomelane
Delessite	Pyrophyllite
Diaspore	Strontianite
Fuchsite	Sulphur
Gibbsite	Wolframite
Jasper	Wollastonite
Lawsonite	

Attention is directed to the Mineral Determination Tables (Appendix I, p. 473), by which means it is hoped that considerable help will be afforded the student in rapidly "running down" species of which he is doubtful. The method of working with these tables is explained in that appendix. Also, in Appendix II (p. 486), a list is given of Rock-forming Minerals as yet unrecorded from Detrital Sediments (excluding Recent Deposits, Alluvials, etc.), but to be anticipated as research proceeds; such species may be expected to occur in mineral assemblages characteristic of particular petrographic provinces.

The significance of mineral associations, index-species, etc., in connexion with diagnosis is to be noted, and receives full discussion on pp. 427-28.

ACTINOLITE. [Fig. 19. Pl. I.

Chem. Comp. $\text{Ca}(\text{Mg}, \text{Fe})_3(\text{SiO}_3)_4$.

System. Monoclinic.

Habit. Slender prisms, often euhedral.

Structure. Crystalline; individual crystals or fibrous aggregates.

Cleavage. Perfect parallel to (110), sometimes observed parallel to (100).

Fracture. Irregular.

Hardness. 5.

Spec. Grav. 2.99.

Lustre. Vitreous.

Colour. Bright green to grey-green; yellow. Transparent.

Mag. Prop. Weakly magnetic.

Elect. Prop. Moderate conductor.

*Opt. Prop.** R.I. high, $\alpha = 1.6116$, $\beta = 1.6270$, $\gamma = 1.6387$. Birefringence medium, $\gamma - \alpha = 0.0271$. Optically biaxial, negative. Optic axial plane parallel to (010). $Bx \cap Z$ inclined at low angle to c axis: extinction angle varies from 8° to 15° ; normally 8° to 12° . $2V = 81^\circ 27'$. Prismatic grains slow $\parallel$ to length. $Y \parallel b$, $Z \wedge c = 15^\circ$. Pleochroism moderate to weak: $X = \text{yellow}$, $Y = \text{green}$, $Z = \text{green}$. Maximum absorption when vibrations are parallel to trace of Z . Dispersion, $\rho < \nu$.

Characters in Sediments. Usually as distinctive yellowish-green, fibrous aggregates or single grains, some individuals being weakly pleochroic, others showing no reaction in this respect. The detrital varieties usually have a low extinction angle; they frequently show alteration to chloritic matter, and contain iron-ore inclusions.

* N.B.—Throughout this book, R.I. is quoted for yellow light unless otherwise stated. Exhaustive data of this and other properties should be sought in standard texts by J. D. Dana, J. P. Iddings, E. S. Larsen and N. H. and A. N. Winchell, whose works, frequently consulted and referred to in this volume, are invaluable to all students of mineralogy.

Occurrence. New Red Sandstone of the West of England;¹ Upper Lias—Lower Inferior Oolite sands of the West of England;² Thanet Sands and Reading Beds of the London Basin;³ Miocene sands of Los Angeles Basin, S. California and other foreign examples rich in amphibole minerals;⁴ later Tertiary deposits of the East of England;⁵ alluvium of R. Tigris;⁴ the Loess.⁶

Possible Sources of Derivation. Crystalline schists; granular or massive metamorphic rocks; secondary alteration product of ferromagnesian silicates in igneous rocks.

REMARKS.—Not a common mineral in detrital sediments unless *all* types of fibrous hornblende are designated as actinolite.

¹ H. H. Thomas, *Q.J.G.S.*, lxx., 1909, p. 235.

² P. G. H. Boswell, *Geol. Mag.*, lxi., 1924, p. 252.

³ P. G. H. Boswell, *Q.J.G.S.*, lxxi., 1915, table IV.

⁴ Author's observations.

⁵ I. S. Double, *Proc. Geol. Assoc.*, xxxv., 1924, p. 335.

⁶ A. Viglino & G. Capeder, *Boll. Soc. geol. ital.*, xvii., 1898, pp. 81-84.

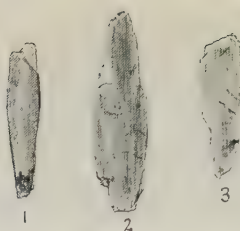


FIG. 19. ACTINOLITE.

1, 2 Recent Sand, River Tigris, Iraq. [x 40.] 3. Shore Sand, Kynance, Cornwall. [x 4.]

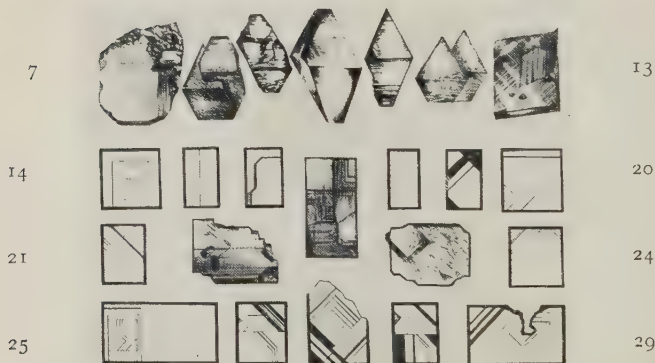
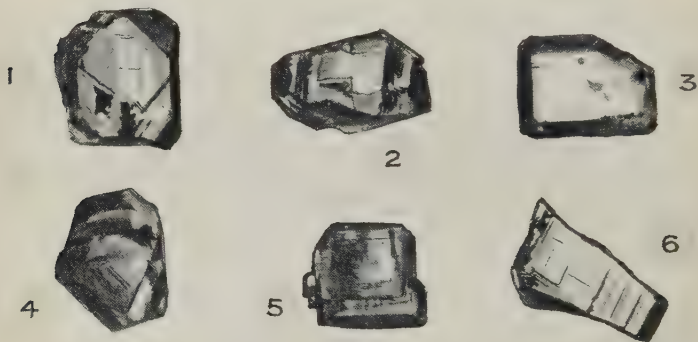


FIG. 20. ANATASE.

- 1, 2, 3, 6. Pliocene Sands, St. Keverne, Cornwall [1, 3, x 120; 2, 6, x 70.]
 4, 5. Tunbridge Wells Sand, Tunbridge Wells, Kent. [x 70.]
 7-29. Typical Crystals and Fragments of Dartmoor Anatase. (From Brush-drawings by A. Brammell.) Grade-size, 0.2-1.4 mm.
 7-13. Octahedrite. Unit pyramid, etc
 14-29. Tabular, basal plane and (111), showing geometric patterning.

ANATASE (Octahedrite). [Fig. 20. Pl. I.]

Chem. Comp. TiO_2 . Oxide of Titanium.

System. Tetragonal.

Habit. Bipyramidal, acute or obtuse, often tabular.

Structure. Crystalline, rarely massive.

Cleavage. Perfect parallel to (001) and (111).

Fracture. Subconchoidal, uneven.

Hardness. 5.5 to 6.

Spec. Grav. 3.82 to 3.95.

Lustre. Adamantine, submetallic.

Colour. Yellow, brown, indigo-blue, black. Transparent to opaque.

Mag. Prop. Non-magnetic.

Elect. Prop. Moderately good conductor.

Opt. Prop. R.I. very high, $\omega = 2.5618$, $\epsilon = 2.4886$.

Birefringence high, $\omega - \epsilon = 0.0732$. Optically uniaxial, negative. Non-pleochroic except in thick grains: ω = pale blue or yellow, ϵ = dark blue or orange. Basal sections isotropic. Strong dispersion. Occasionally in the darker coloured varieties a biaxial figure with small optic axial angle is observed.

Characters in Sediments. Tabular (basal) grains are most common (001), often bevelled by (111) faces. Such grains exhibit interference figure. Parallel intergrowth of tabular varieties common. Pyramidal forms, simple or compound, also observed; these may show striations parallel to intersection with prism (110). Less common are the angular cleavage flakes or irregularly fractured grains. Two distinct coloured varieties are met with, the yellow or yellow-brown, and the indigo-blue or greenish-blue types. Dark coloured grains are almost metallic and opaque. Inclusions of quartz, tourmaline, zircon, rutile, cassiterite, iron-ores, have been noted. Zoning or "geometric patterning" frequent in some developments: see under remarks on p. 124. Both primary and secondary grains occur, sometimes in the same deposit; the latter are probably derived *in situ* from the decomposition of titaniferous minerals such as ilmenite, and usually show marked euhedrism. The former are detrital, evidenced by a certain degree of wear (rounding) consequent on prolonged abrasion.

Occurrence. In Ordovician sediments;¹ in Devonian grits, slates, etc., of the Torquay district, Devon;² in the Old Red Sandstone of the West Midlands;³ in the Permian-Triassic rocks of the Midlands;⁴ in the Bunter Pebble Bed of the West of England;⁵ in the New Red Sandstone of the West of England;⁶ in the Upper Lias—Lower Inferior Oolite sands of the West of England;⁷ in the Kellaways Rock (Oxfordian) of the Peterborough District;⁸ in the Wealden Sands (Lower Cretaceous) of Tunbridge Wells and other areas in the Weald;⁹ in Cretaceous sands of the Haldon Hills, etc., West of England;¹⁰ in the Bagshot Beds (Eocene) of Essex;¹¹ in the Pliocene sands, St. Keverne, Cornwall;¹² in later Tertiary deposits of Eastern England;¹³ in alluvial sands, Dartmoor, Devon;^{14, 15} and in certain surface deposits of S.E. Devon.¹⁶

Possible Sources of Derivation. Crystalline igneous and metamorphic rocks; more commonly authigenic, derived *in situ* from decomposition of ilmenite or other titaniferous species: see reference ¹⁴, p. 125.

REMARKS. — The mineralogy and geochemistry of anatase have been very fully discussed by A. Brammall and H. F. Harwood in connexion with its occurrence at Dartmoor, while in a later contribution, the former author figures and describes some beautiful examples of both zoned tabular and pyramidal types found in Dartmoor detrital deposits; both these papers should be consulted for this interesting mineral (see references ^{14, 15}, p. 125).

¹ P. G. H. Boswell, *Proc. Liverpool Geol. Soc.*, xiv., 1924, p. 14.

² W. G. Shannon, *Proc. Geol. Assoc.*, xxxix., 1928, pp. 137-153.

³ W. F. Fleet, *Geol. Mag.*, lxiii., 1926, p. 513.

⁴ W. F. Fleet, *Proc. Geol. Assoc.*, xxxviii., 1927, pp. 1-48.

⁵ H. H. Thomas, *Q.J.G.S.*, lviii., 1902, p. 622 & plate xxxii.

⁶ H. H. Thomas, *Q.J.G.S.*, lxx., 1909, p. 231.

⁷ P. G. H. Boswell, *Geol. Mag.*, lxi., 1924, p. 254.

⁸ E. Neaverson, *Proc. Geol. Assoc.*, xxxvi., 1925, pp. 23-37.

⁹ H. B. Milner, *Proc. Geol. Assoc.*, xxxiv., 1923, plate 5; also xxxiv., 1923, pp. 290-292; also xxxvi., 1925, p. 315.

¹⁰ P. G. H. Boswell, *Q.J.G.S.*, lxxix., 1923, pp. 209 & 218.

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- ¹¹ S. W. Wooldridge, *Proc. Geol. Assoc.*, xxxv., 1924, p. 377.
¹² H. B. Milner, *Q.J.G.S.*, lxxviii., 1922, p. 363.
¹³ I. S. Double, *Proc. Geol. Assoc.*, xxxv., 1924, p. 338.
¹⁴ A. Brammall & H. F. Harwood, *Mineralogical Mag.*, xx.,
1923, pp. 20-26.
¹⁵ A. Brammall, *Proc. Geol. Assoc.*, xxxix., 1928, pp. 30-31.
¹⁶ W. G. Shannon, *Geol. Mag.*, lxiv., 1927, p. 147.

ANDALUSITE. [Fig. 21. Pl. II.]

Chem. Comp. $\text{Al}_2\text{O}_3 \cdot \text{SiO}_2$. Fe and Mn may be present.

System. Orthorhombic.

Habit. Prismatic, rarely euhedral.

Structure. Usually crystalline.

Cleavage. Distinct parallel to (110), imperfect parallel to (100), more rarely parallel to (010).

Fracture. Uneven and irregular.

Hardness. 7.5.

Spec. Grav. 3.16 to 3.20.

Lustre. Vitreous.

Colour. Colourless, white, and pale shades of red, green, brown and violet. Transparent to translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Bad conductor.

Opt. Prop. R.I. high, $\alpha = 1.632$, $\beta = 1.638$, $\gamma = 1.643$.

Birefringence low, $\gamma - \alpha = 0.011$. Optically biaxial, negative. $2V = 85^\circ$. Length fast. Optic axial plane parallel to (010). Bxa normal to (001). $Bxa = X \parallel c$; $Y \parallel b$, $Z \parallel a$. Straight extinction parallel to prism-edge. Pleochroism intense in some varieties; maximum absorption $\parallel$ to length when vibrations of polariser are E-W; $X > Y > Z$; Y and Z colourless, X rose or blood-red.

Characters in Sediments. Colourless, "glassy"; sometimes with pinkish tinge; grains very variable in form; commonly irregular and subangular, but prismatic types also met with. Frequently shows presence of inclusions of graphite or carbonaceous matter,[†] also alteration products such as muscovite or kaolinite, all causing a turbid appearance of the mineral. These features and its negative sign serve to differentiate andalusite from topaz (with which it may sometimes be confused), but the pleochroism of the former, when present, is an infallible guide. This pleochroism is best seen in prismatic grains orientated in an east-west position (*i.e.*, $\parallel$ short axis of polariser).

Occurrence. In the Millstone Grit of Yorkshire;¹ in Cretaceous and Eocene sands of the Oxford district;² in

[†] Chiastolite: see page 154.

¹ A. Gilligan, *Q.J.G.S.*, lxxv., 1919-20, p. 251 *et seq.*

² G. M. Davies, *Mineralogical Mag.*, xvii., 1915, pp. 218-220.

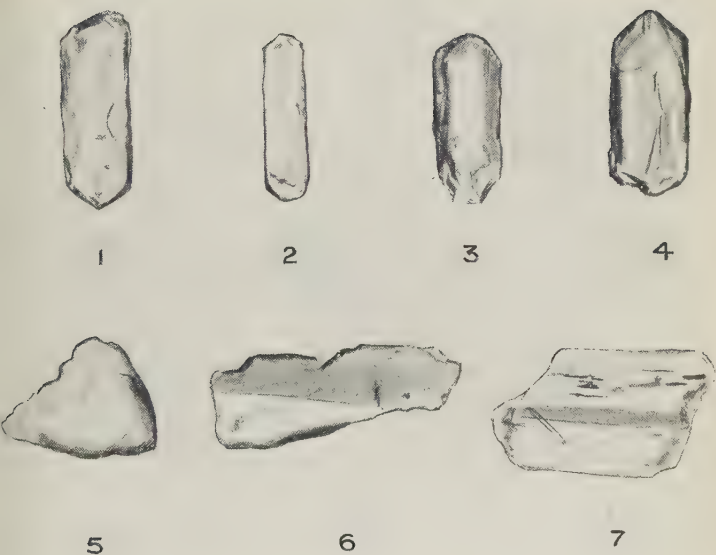


FIG. 21. ANDALUSITE.

- 1-4. Pliocene Sands, Cornwall.
 5. Blown Sands, Newgale, Pembrokeshire.
 6, 7. Pliocene Sands, Cornwall. [All x 60.]

the Cretaceous and Tertiary deposits of the West of England;¹ in the Pliocene deposits of St. Keverne, Cornwall;² in the later Tertiary deposits of the East of England;³ in the Pliocene deposits of Sanderstead, Surrey;⁴ in the Dartmoor detritals;⁵ in the surface deposits of S.E. Devon.⁶

Possible Sources of Derivation. Granitic and metamorphic rocks.

REMARKS.—At one time detrital andalusite was thought to be restricted to Tertiary deposits in the British Isles, but as the references above show, it ranges back at least as far as Cretaceous sediments, probably to Palæozoic. It certainly gets extremely rare with increasing geological age of sedimentary rocks, and may be looked for almost universally in Pliocene deposits, according to the author's observations. See also references to Chiasolite occurrences on page 154, paragraph on page 441, and reference ⁷ below.

¹ P. G. H. Boswell, *Q.J.G.S.*, lxxix., 1923, pp. 205-230.

² H. B. Milner, *Q.J.G.S.*, lxxviii., 1922, p. 363.

³ I. S. Double, *Proc. Geol. Assoc.*, xxxv., 1924, p. 339.

⁴ F. Gossling & S. W. Wooldridge, *Proc. Geol. Assoc.*, xxxvii., 1926, pp. 92-101.

⁵ A. Brammall, *Proc. Geol. Assoc.*, xxxiix., 1928, pp. 27-48.

⁶ W. G. Shannon, *Geol. Mag.*, lxiv., 1927, pp. 145-153.

⁷ P. G. H. Boswell, "The Rarer Minerals of British Sedimentary Rocks," *Trans. Geol. Soc. Glasgow*, xviii., 1926-27, pp. 133-4.

ANHYDRITE [Fig. 22. Pl. III.]

Chem. Comp. CaSO_4 .

System. Orthorhombic.

Habit. Prismatic, tabular, fibrous (radial, spherulitic), granular, and as rectangular cleavage flakes. Also twinned about (012) and (101).

Structure. Crystalline, massive; curvilinear.

Cleavage. Three pinacoidal directions: very perfect parallel to (001) and (010); less perfect parallel to (100); the three when developed give rise to square-shaped flakes.

Fracture. Irregular, splintery.

Hardness. 3 to 3.5.

Spec. Grav. 2.899 to 2.985. (Note difference from Gypsum, p. 187.)

Lustre. Pearly on (001) flakes; glassy on (010) and (100) flakes. Sometimes resinous.

Colour. Colourless, white, grey, pink or bluish-white. Colourless in thin grains or sections.

Mag. Prop. Non-magnetic.

Elect. Prop. Poor conductor.

Opt. Prop. R.I. variable, $\alpha = 1.5693$ - 1.571 , $\beta = 1.5752$ - 1.5760 , $\gamma = 1.6130$ - 1.6138 . Birefringence high, $\gamma - \alpha = 0.0437$ - 0.0428 . Biaxial positive. $2V = \pm 42^\circ$, axial angle generally large. Optic axial plane parallel to (010). Bxa normal to (100). $Bxa = Z$. $X \parallel c$, $Y \parallel b$, $Z \parallel a$. Straight extinction. Non-pleochroic. Dispersion $\rho < \nu$.

Characters in Sediments. Extremely variable in form, some of the principal varieties shown in plate III opposite. An interesting, but little known species as free crystalline grains. Diagnosed chiefly by its S.G., R.I. (a certain amount of "twinkling" is observed in many examples), cleavages and positive optical character. Liable to confusion with barite, sometimes kyanite, topaz, sillimanite, possibly enstatite. Distinguish by careful S.G. and optical tests, also (if necessary) with HCl which causes no effervescence, thus differentiating it from all carbonates. Well cleaved, rectangular grains exhibit remarkable cubic appearance and are unique in development. Note that

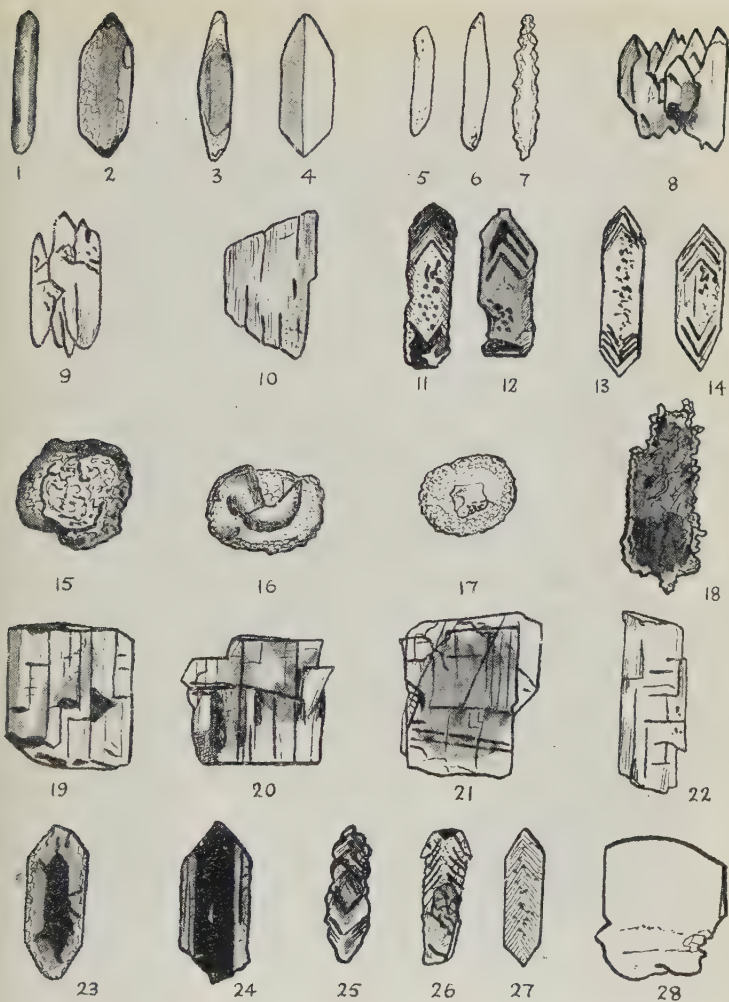


FIG. 22. ANHYDRITE.

All from the Lower Fars (Miocene) of Iraq and Persia

- 1-4. Euhedra. 5-7. "Denticular" types.
 8-9. Composite "sheaf" type. 10. Fibrous type.
 11-14. Zoned types. 15-17. "Oolite" types.
 18. "Etched" or "ragged" type.
 19-21. Rectangular (Pseudo-cubic cleaved) types.
 22. "Kyanite" type. 23-24. With dark cores.
 25-27. "Herring-bone" type. 28. Glass-clear grain. [All x 25.]

N.B.—Nos. 10-14, 18, 25-27 show partial alteration to gypsum.

(001) cleavage flakes will yield a biaxial figure (emergence of bxo) which is "central," in contrast with figure yielded by calcite (eccentric or partial). Aggregates and compound grains also observed. Inclusions of iron-ores common; zoning developed in occasional types; see *fig. 22*, nos. 11-14. In appropriate circumstances anhydrite grains exhibit every stage in alteration to gypsum, the most notable features being loss of crystal form and relief (decreased R.I.), change of optical properties, and sometimes the formation of definite gypsum crystals (p. 188).

Occurrence. In Miocene sands and marls, Iraq and Persia.¹

Possible Sources of Derivation. Invariably authigenic; occurs mainly in association with limestones from which it can be formed by replacement (metasomatism). Also occurs with rock-salt and, contrary to usual belief, co-exists with gypsum in the same deposit.

REMARKS. -- Haloanhydrite is a peculiar species compounded of rock-salt and anhydrite.

¹ Author's observations.

APATITE. [Fig. 23. Pl. IV.]

Chem. Comp. Fluor-Apatite, $\text{Ca}_4(\text{CaF})(\text{PO}_4)_3$. Chlor-Apatite, $\text{Ca}_4(\text{CaCl})(\text{PO}_4)_3$. Intermediate compounds occur with both F and Cl. Also traces of Mn, Di, Ce and Hydroxyl.

System. Hexagonal.

Habit. Prismatic, bipyramidal, or with basal pinacoid.

Structure. Usually crystalline, sometimes acicular, massive, granular or compact.

Cleavage. Imperfect parallel to (0001); more rarely parallel to (10 $\bar{1}$ 0).

Fracture. Uneven, conchoidal.

Hardness. 5. Less in massive varieties (4.5).

Spec. Grav. 3.17 to 3.23.

Lustre. Vitreous to sub-resinous.

Colour. Commonly white, colourless or shades of green. Transparent.

Mag. Prop. Non-magnetic.

Elect. Prop. Weak conductor.

Opt. Prop. R.I. high, $\omega = 1.6335$, $\epsilon = 1.6316$.

Birefringence very low, $\omega - \epsilon = 0.0019$. Optically uniaxial, negative. Sometimes exhibits pseudo-biaxial figure. Some coloured varieties weakly pleochroic. Straight extinction. Length fast. Basal sections isotropic.

Characters in Sediments. Rounded elongated prismatic, or "egg-shaped" grains most common, sometimes with minute indeterminable inclusions arranged parallel to the principal axis: these may be fluid. Grains, frequently very small, often showing evidence of solution. Some varieties exhibit dark purple, pleochroic cores or nuclei: see general references, p. 131.

Occurrence. In the Old Red Sandstone, Cardiff area;¹ in certain Palæozoic rocks of the English Midlands;² in the Devonian rocks of the Torquay district;³ in the Old Red Sandstone of the West Midlands;⁴ in the Permo-

¹ A. Heard & R. Davies, *Q.J.G.S.*, lxxx., 1924, p. 501.

² W. F. Fleet, *Geol. Mag.*, lxii., 1925, pp. 102, 106, 110, 113, 116, 120, 123.

³ W. G. Shannon, *Proc. Geol. Assoc.*, xxxix., 1928, p. 141.

⁴ W. F. Fleet, *Geol. Mag.*, lxiii., 1926, p. 513.

Triassic rocks of the Midlands;¹ in the Lower Permian rocks of N. England;² in the Bunter Pebble Bed, West of England;³ in the Upper Lias—Inferior Oolite of the West of England;⁴ in the Upper Greensand of the Haldon Hills, Devon;⁵ in the Bagshot Beds of Essex;⁶ in the later Tertiary deposits of East England;⁷ in the Dartmoor detritals;⁸ in the surface deposits of S.E. Devon.⁹

Possible Sources of Derivation. Igneous rocks, especially granites and syenites.

REMARK3.—Apatite is probably far commoner in sediments than existing records would lead one to believe. It is liable to be lost by solution, either natural or during acid-cleaning of the sediment prior to separation, while its possible confusion with other colourless minerals is not an insignificant factor (see Table III, p. 479). The detrital form, R.I., low birefringence, all serve to differentiate the species, though a confirmatory test for phosphate is always resorted to where a number of grains occur whose identity as apatite is suspected.

¹ W. F. Fleet, *Proc. Geol. Assoc.*, xxxviii., 1927, pp. 1-48.

² H. C. Versey, *Proc. Yorks. Geol. Soc.*, 1925, and *Geol. Mag.*, 1924, pp. 380-381.

³ H. H. Thomas, *Q.J.G.S.*, lviii., 1902, p. 621.

⁴ P. G. H. Boswell, *Geol. Mag.*, lxi., 1924, p. 257.

⁵ P. G. H. Boswell, *Q.J.G.S.*, lxxix., 1923, p. 226.

⁶ S. W. Wooldridge, *Proc. Geol. Assoc.*, xxxv., 1924, pp. 359-383.

⁷ I. S. Double, *Proc. Geol. Assoc.*, xxxv., 1924, p. 338.

⁸ A. Brammall, *Proc. Geol. Assoc.*, xxxix., 1928, p. 39.

⁹ W. G. Shannon, *Geol. Mag.*, lxiv., 1927, p. 147.

General References.

W. F. Fleet & F. Smithson, "On the Occurrence of Dark Apatite in some British Rocks," *Geol. Mag.*, lxxv., 1928, p. 6.

W. Mackie, "The Apatites in Sedimentary Rocks as Indicators of the Amount of Atmospheric Carbonic Acid in the Periods of Deposit," *Trans. Geol. Soc. Glasgow*, xvii., 1926, pp. 407-421.

A. W. Groves & A. E. Maurant, "Inclusions in the Apatites of Some Igneous Rocks." (In course of publication, *Mineralogical Society*, 1929).

ARAGONITE.

Chem. Comp. CaCO_3 .

System. Orthorhombic.

Habit. Euhedral, acicular, and as interpenetration twins resulting in pseudo-hexagonal "platy" forms.

Structure. Crystalline, globular, earthy.

Cleavage. Good parallel to (010); imperfect parallel to (110) and (011).

Fracture. Subconchoidal.

Hardness. 3.5 to 4.

Spec. Grav. 2.93 to 2.95.

Lustre. Vitreous, resinous on fractured surfaces.

Colour. Colourless, grey, greyish-yellow, green, mauve.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. both lower and higher than Canada balsam, as in calcite, $\alpha = 1.5301$, $\beta = 1.6816$, $\gamma = 1.6859$. Birefringence high, $\gamma - \alpha = 0.1558$. Optically biaxial, negative. Optic axial plane parallel to (100). $Bxa = X \parallel c$, normal to (001); $Z \parallel b$. Length fast. Optic axial angle small, $2V = 18^\circ$, $2E = 30^\circ$. Weak dispersion, $\rho < \nu$. Straight extinction in prismatic grains. Non-pleochroic. Characteristic "twinkling" as in calcite.

Characters in Sediments. Detrital aragonite is extremely rare and the irregularly-shaped fragments met with in certain sediments are usually ascribable to broken lamellibranch shells or possibly gasteropod remains. The porcellanous forms of *foraminifera* are mainly of aragonite. Otherwise it is difficult to be certain of definite diagnosis of this mineral by microscopical means alone, and chemical tests are desirable if possible, chiefly to distinguish it from calcite. See under Remarks, p. 133.

Occurrence. As fragments of probable organic origin in many Tertiary and Recent deposits, e.g., Pliocene of Walton-on-Naze, Essex.¹ Also listed by Boswell.²

¹ Author's observations.

² P. G. H. Boswell, *Proc. Liverpool Geol. Soc.*, xiii., 1923, p. 268.

Possible Sources of Derivation. Where not of organic origin almost certainly authigenic and associated with limestone and gypsum; also occurs in vesicles in basalts and various lavas to which it may be locally traced in some instances.

REMARKS.—Aragonite is distinguished from calcite by its higher S.G. and absence of rhombohedral cleavage, also by Meigen's reaction:—boil grains with $\text{Co}(\text{NO}_3)_2$ when a lilac or violet colour quickly appears. Another test is to treat the $\text{Co}(\text{NO}_3)_2$ stained grains with ammonium sulphide solution, when cobalt sulphide is precipitated on the aragonite grains more thickly than on any associated calcite grains, resulting in dense black aggregates on the former species.

AUGITE. [Fig. 24. Pl. IV.]

Chem. Comp. Silicate of lime, magnesium, iron and aluminium, etc. Also titaniferous varieties.

System. Monoclinic.

Habit. Commonly prismatic, with varying terminations.

Structure. Usually crystalline, sometimes granular.

Cleavage. Good parallel to (110), more rarely parallel to (100). (001) parting frequently observed, evidenced by twin lamellæ, the latter also common || (100).

Fracture. Uneven.

Hardness. 5 to 6.

Spec. Grav. 3.2 to 3.6 (varies with composition).

Lustre. Vitreous, sometimes resinous.

Colour. Shades of yellowish-green, green to blackish-green. Sometimes brown.

Mag. Prop. Moderately magnetic; varies with the amount of iron present.

Elect. Prop. Moderately good conductor.

Opt. Prop. R.I. very high, $\alpha = 1.712$, $\beta = 1.717$, $\gamma = 1.733$.

Birefringence high, $\gamma - \alpha = 0.021$. Optically biaxial, positive. Optic axial plane parallel to (010). $Y \parallel b$.

$Bxa = Z$ inclined at $38^\circ - 54^\circ$ to c axis. $2V = 61^\circ \dagger$.

Oblique extinction angle $35^\circ - 54^\circ$ (varies). Slightly pleochroic in some titaniferous varieties. Dispersion $\rho > \nu$.

Characters in Sediments. Grains usually either rounded prismatic forms or irregular cleavage fragments, the latter often showing the emergence of an optic axis. Fractured or "broken" grains are sometimes met with which are very characteristic of the particular horizon at which they occur. Diagnosed chiefly by its colour and high extinction angle, and anticipated where other pyroxenes, also olivine, are prevalent.

Occurrence. In the Old Red Sandstone of the West Midlands;¹ in the Permo-Triassic rocks of the Midlands;²

[†] Varies, as with other optical properties, with the amount of Al_2O_3 and Fe_2O_3 present.

¹ W. F. Fleet, *Geol. Mag.*, lxiii., 1926, p. 513.

² W. F. Fleet, *Proc. Geol. Assoc.*, xxxviii., 1927, p. 6.

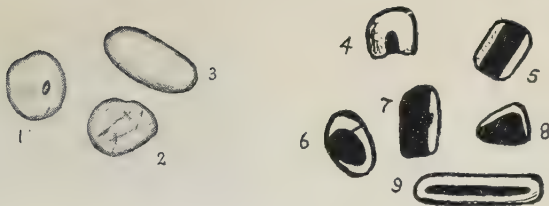


FIG. 23. APATITE.

1-3. Up. Mottled Sandstone (Bunter), Wores. [x 90.] 4-9. Keuper Sandstone, Aldborough, Yorkshire. (From slide by F. Smithson.) [x 20.]

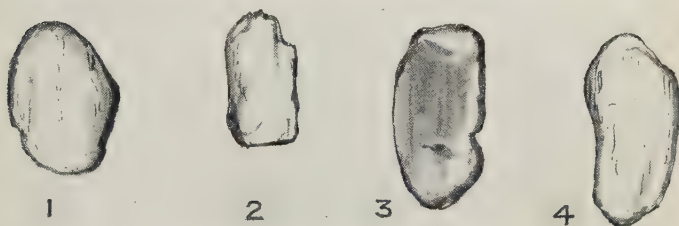


FIG. 24. AUGITE. 1, 2. Recent Sands, Rosslare, Co. Wexford; Cape Verde Is. 4. Blown Sands, Newgale, Pembrokeshire. [All x 70.]



FIG. 25. AXINITE. 1-3. Shore Sand, near Carrick Du, St. Ives, Cornwall. [x 40.]

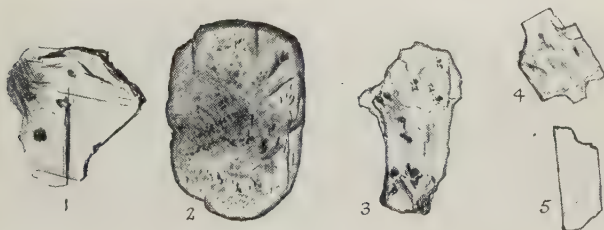


FIG. 26. BARITE. 1, 2. Shore Sand, Co. Cork, I.F.S. [x 35.] 3-5. Keuper Sand, Alderley Edge, Cheshire. [x 35.]

in surface deposits of S.E. Devon;¹ in the deep sea deposits of the Atlantic Ocean;² in the deep sea deposits of the Pacific Ocean;³ in the dune sands of South Wales;⁴ in shore sand at Rosslare, Co. Wexford;⁵ in shore sand of Cape Verde Islands;⁶ in blown sand at Newgale, Pembrokeshire.⁷

Possible Sources of Derivation. Intermediate and basic igneous rocks.

REMARKS.—As would be expected, augite is somewhat haphazard in its occurrence in sediments, though it is frequently very common in deep-sea deposits and shore sands fed by disintegrated volcanic materials. Sometimes it is difficult to decide between augite and diopside in diagnosis; there is much to be said for restricting the latter label to the pale green or colourless grains found in pyroxene-rich samples, and whose striking feature is often their surprising freshness, in contrast to the yellower-green augite which frequently exhibits traces of decomposition or dusky inclusions of iron-ores. See also Diopside, p. 166, and Ægirine, p. 260.

¹ W. G. Shannon, *Geol. Mag.*, lxiv., 1927, p. 147.

² J. Murray & J. Chumley, *Trans. Roy. Soc. Edinburgh*, liv., 1924, pp. i.-ix., 1-252.

³ J. Murray, *Geographical Journ.*, xiv., 1902, pp. 691-711.

⁴ A. Stuart, *Proc. Geol. Assoc.*, xxxv., 1924, p. 323.

⁵ Author's observations.

⁶ Noted by G. M. Fart.

⁷ Author's observations.

AXINITE. [Fig. 25. Pl. IV.]

Chem. Comp. $\text{Ca}_7\text{Al}_4\text{B}_2(\text{SiO}_4)_8$. Mn, Fe and Mg may also be present.

System. Triclinic.

Habit. Diamond- or wedge-shaped crystals, sometimes euhedral, rarely prismatic; flattened.

Structure. Crystalline, rarely lamellar or granular.

Cleavage. Distinct parallel to (010); sometimes parallel to (001) and (1 $\bar{3}$ 0).

Fracture. Conchoidal.

Hardness. 6.5 to 7.

Spec. Grav. 3.271 to 3.294.

Lustre. Vitreous.

Colour. Pinkish-brown to red, "plum," greyish-yellow; shades of mauve and yellowish-red; rarely colourless.

Mag. Prop. Non-magnetic.

Elect. Prop. Poor conductor.

Opt. Prop. R.I. moderately high, $\alpha = 1.6720$, $\beta = 1.6779$, $\gamma = 1.6810$. Birefringence low, $\gamma - \alpha = 0.009$. Optically biaxial, negative. Trace of optic axial plane inclined 40° to edge (111) ($1\bar{1}0$) and $24^\circ 40'$ to (111) ($1\bar{1}1$), Des Cloizeaux. $Bxa = X$ practically normal to (111). $2V = 71^\circ 38'$ (red). Strong dispersion, $\rho < \nu$. Pleochroism moderate: X = pale green, olive green, Y = dark blue or violet, Z = brown; only observed in thick grains.

Characters in Sediments. Occurs in irregular or rounded, diamond-shaped grains of characteristic colour, usually a delicate shade of mauve or pink. The grains reveal the presence of small conchoidal fractures, which are characteristic. Detrital axinite is for the most part non-pleochroic, unless the grains are large. Grains frequently fail to extinguish in any position.

Occurrence. Observed only in Recent Sands, in particular the shore sands at various points along the Land's End — St. Ives coast, Cornwall.¹

Possible Sources of Derivation. Metamorphosed basic igneous rocks (pneumatolytic modifications); cavities in granitic rocks.

REMARKS.—A local species to be anticipated in recent sediments rather than in those of greater age. Often associated with pyroxene, amphibole, calcite and sulphide ores.

¹ Author's observations.

BARITE. [Fig. 26. Pl. IV.]

Chem. Comp. BaSO_4 .

System. Orthorhombic.

Habit. Prismatic, with basal plane strongly developed.

Structure. Crystalline, massive or lamellar.

Cleavage. Perfect parallel to (001) and (110); imperfect parallel to (010).

Fracture. Uneven.

Hardness. 2.5 to 3.5.

Spec. Grav. 4.5.

Lustre. Vitreous, pearly, often combined with "cloudy" appearance.

Colour. Colourless, bluish-white or yellow. Transparent to translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Bad conductor.

Opt. Prop. R.I. high, $\alpha = 1.636$, $\beta = 1.637$, $\gamma = 1.648$.

Birefringence low, $\gamma - \alpha = 0.012$. Optically biaxial, positive. Optic axial plane parallel to (010). Length slow. $Bxa = Z$ normal to (100). $2V = 37^\circ 30'$. $X \parallel c$, $Y \parallel b$, $Z \parallel a$. Prismatic grains give straight extinction. Cleavage grains may show emergence of the bxo . Dispersion weak, $\rho < \nu$.

Characters in Sediments. Fragments of this mineral are varied in character; the normal type is entirely irregular, angular, and determined chiefly by fracture, cleavage or the original shape of the interstice which it filled as a cementing medium. Sharply angular cleavage fragments are common, but seldom yield good interference figure. Grains rarely show rounding, though they may be intensely fractured. Diagnosed chiefly by its high S.G., and optical properties, also by its "patchy" lustre, brown staining and varied inclusions (iron-ores).

Occurrence. In the Old Red Sandstone of the West Midlands;¹ in the Permo-Triassic rocks of the Midlands;² in the Lower Permian rocks of Northern England;³ in

¹ W. F. Fleet, *Geol. Mag.*, lxiii., 1926, p. 512.

² W. F. Fleet, *Proc. Geol. Assoc.*, xxxviii., 1927, p. 6.

³ H. C. Versey, *Proc. Yorks. Geol. Soc.*, xx., 1925, pp. 200-

the Keuper Sands, Alderley Edge, Cheshire;¹ in the New Red Sandstone of West England;² in the Fuller's Earth and Folkestone Beds (Lower Greensand) of Surrey and Kent respectively;³ in the London Clay of Sheppey;⁴ in river sands from the Ure and Ouse;⁵ in shore sands from Co. Cork, I.F.S.⁶

Possible Sources of Derivation. From sandstones, in which it acts as the cementing medium; from veins in limestones associated with calcite; from the gangue of metalliferous veins or from massive deposits of barite associated with calcareous sediments.

REMARKS.—Rarely met with as detrital grains; Versey has described both authigenic and allogenic occurrences;⁷ presence in residue usually due to the disintegration of the cementing medium of a sand on treatment of the latter for "heavy" mineral analysis. Distinguish from anhydrite by the forms and cleavages of that mineral. Barite has the higher S.G., and the characteristic lustre noted above.

¹ Author's observations.

² H. H. Thomas, *Q.J.G.S.*, lxx., 1909, p. 234.

^{3, 4} G. M. Davies, *Proc. Croydon Nat. Hist. Soc.*, 1915-16, pp. 93-4

⁵ S. Melmore, *Geol. Mag.*, lxiii., 1926, pp. 268-271.

⁶ Author's observations.

⁷ *Op. cit.*

BIOTITE.

[Fig. 27. Pl. V.]

Chem. Comp. Silicate of aluminium, magnesium, iron and potassium.

System. Monoclinic.

Habit. Tabular; short prismatic crystals with well-developed basal planes. Frequently twinned.

Structure. Irregular, but strongly laminated. Crystals rare.

Cleavage. Perfect basal (001).

Fracture. Uneven.

Hardness. 2.5 to 3.

Spec. Grav. 2.79 to 3.16.

Lustre. Vitreous, resinous or dull.

Colour. Dark green, brown to blackish-brown.

Mag. Prop. Moderately magnetic.

Elect. Prop. Moderate conductor.

Opt. Prop. R.I. low, $\alpha = 1.504$, $\beta = 1.589$, $\gamma = 1.589$.

Birefringence high, $\gamma - \alpha = 0.085$. Optically biaxial, negative. $Bxa = X$ normal to (001); optic axial angle small in certain varieties, giving pseudo-uniaxial interference figure. Pleochroism varies with composition, being strongest in the deep brown facies (Phlogopite): brown to dull yellow or colourless ($X < Y$ and Z).

Characters in Sediments. Occurs mostly as brown or yellow cleavage flakes with jagged edges; seldom worn. Pleochroic haloes round crystals of zircon, xenotime, allanite, etc., enclosed in the mica are of frequent occurrence, especially in the deep brown varieties. Other inclusions noted are rutile, anatase and monazite. Striations common. Detrital flakes tend to lie with (001) in the plane of the slide, hence are non-pleochroic. Partial alteration to chloritic matter, producing a "bleached" grain, is commonly observed. Diagnosed almost invariably by its colour, cleavage and biaxial negative figure (of small O.A. angle).

Occurrence. In the Devonian rocks of the Torquay district;¹ in the Grindstones from the Coal Measures,

¹ W. G. Shannon, *Proc. Geol. Assoc.*, xxxix., 1928, p. 141.

Yorkshire;¹ in the Upper Lias—Lower Inferior Oolite sands of West England;² in Bentonite (Cretaceous) of Wyoming, U.S.A.;³ in the Pliocene deposits of Cornwall;⁴ *phlogopite* in Cornish Pliocene;⁵ in the later Tertiary deposits of East England;⁶ in dune sands of South Wales;⁷ in Dartmoor detritals;⁸ in Chalk boulders from the seafloor off the Scottish coast;⁹ in shore sands from Dinard, Brittany, and from White Sand Bay, Cornwall;¹⁰ in marine peat, Union Dock, Liverpool.¹¹

Possible Sources of Derivation. Igneous and metamorphic rocks.

REMARKS.—*Lepidomelane*, a variety of biotite rich in ferric iron, sometimes occurs in recent sediments suitably derived. It is characterized by its higher S.G. (3.2), almost black colour, weak pleochroism, and a rich, blackish-brown pearly lustre. Usually traceable to felspathic igneous rocks of the syenite type, less commonly to metamorphic rocks. For *Phlogopite*, see reference ⁵ below.

¹ H. P. Lewis & W. J. Rees, *Geol. Mag.*, lxiii., 1926, pp. 13-27.

² P. G. H. Boswell, *Geol. Mag.*, lxi., 1924, p. 257.

³ D. F. Hewett, *U.S.G.S., Prof. Paper* 145, 1926, pp. 1-111.

⁴ H. B. Milner, *Q.J.G.S.*, lxxviii., 1922, pp. 364-5.

⁵ P. G. H. Boswell, *Q.J.G.S.*, lxxix., 1923, p. 226.

⁶ I. S. Double, *Proc. Geol. Assoc.*, xxxv., 1924, pp. 341, 343.

⁷ A. Stuart, *Proc. Geol. Assoc.*, xxxv., 1924, p. 323.

⁸ A. Brammall, *Proc. Geol. Assoc.*, xxxix., 1928, p. 46.

⁹ H. H. Thomas in W. Hill, *Proc. Roy. Soc. Edinburgh*, xxxv., 1915, pp. 263-296.

¹⁰ Author's observations.

¹¹ J. Lomas, *Rept. Brit. Assoc.*, 1907 (Leicester), 1908, p. 516.

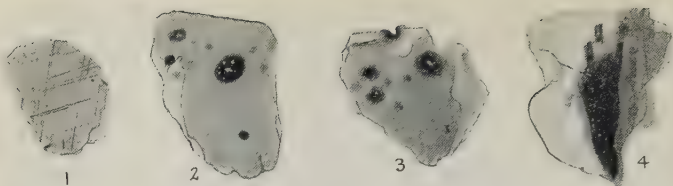


FIG. 27. BIOTITE.

1-3. Shore Sand, Dinard, Brittany. [x 40.]
 4. do. White Sand Bay, Cornwall. [x 70.]



FIG. 28. BROOKITE.

Typical Crystals and Fragments from Dartmoor. (From Brush-drawings by
 A. Brammall.) Grade-size : 0.2-1.4 mm.

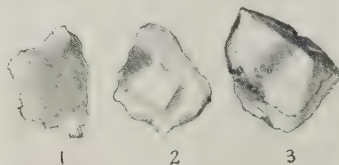


FIG. 30. CALCITE.

1, 2. Upper Greensand, Chaldon Herring, Dorset. [x 80.] 3. Shore
 Sand, Kynance, Cornwall. [x 40.]

BROOKITE. [Fig. 28. Pl. V.]

Chem. Comp. TiO_2 .

System. Orthorhombic.

Habit. Prismatic, tabular, parallel to (100) or pyramidal. Often striated parallel to principal axis.

Structure. Crystalline.

Cleavage. Poor parallel to (110) and (001).

Fracture. Subconchoidal, irregular.

Hardness. 5.5 to 6.

Spec. Grav. 3.87 to 4.084.

Lustre. Resinous, vitreous, submetallic.

Colour. Shades of brown and yellow. Translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Moderate conductor.

Opt. Prop. R.I. very high, $\alpha = 2.5832$, $\beta = 2.5856$, $\gamma = 2.7414$.

Birefringence very high, $\gamma - \alpha = 0.1582$. Optically

biaxial, positive. $Bxa = Z \parallel a$, normal to (100).

Optical properties are anomalous; the optic axial

plane is parallel to (001) for red and yellow

light, and parallel to (010) for green and blue light;

i.e., $Xr \parallel b$, or $Xbl \parallel c$. For intermediate col-

our (yellow-green) brookite is uniaxial and isotropic.

Optic axial angle varies: for red light $2E = 55^\circ$, for

yellow 30° , for green $2E = 34^\circ$, for yellow-green $2E =$

0° . $Z > Y > X$, or $Y > Z > X$. Many crystals fail to

extinguish in any position; some show straight ex-

tinguishment parallel to the principal striæ or prism-edge.

Non-pleochroic as a rule. Dispersion very strong. For

a full and illustrated discussion on the optical properties

of detrital brookite, the reader is referred to reference

⁸, p. 142.

Characters in Sediments. Detrital brookite is a somewhat elusive species. Normally occurs as dusky brown or yellow grains, tabular parallel to (100), while (110) and (010) types are observed. Noteworthy absence of extinction; interference colour change on rotation. Striæ parallel to the principal axis are common, also noted by Brammall parallel to the b-axis, i.e., at right angles to the prominent system. Inclusions are commonly detected, these being "aggregates and stringers of

opaque dust," also in the Dartmoor types, rutile, tourmaline, rarely topaz and globular isotropic bodies. *Occurrence.* In the Bunter Pebble Bed of the West of England;¹ in the New Red Sandstone of the West of England;² in the Upper Lias—Lower Inferior Oolite sands of the West of England;³ in the Greensand of the Haldon Hills, Devon;⁴ in the Oligocene beds of the Bovey Basin, Devon;⁵ in the Pliocene deposits of West Cornwall;⁶ in the later Tertiary deposits (Red Crag, Chillesford Beds, etc.) of East England;⁷ in Dartmoor detritals.⁸

Possible Sources of Derivation. Acid igneous and crystalline metamorphic rocks; from the pneumatolysis and tourmalinization of titaniferous biotite. See Brammall, *op. cit.* p. 47, also this volume, under ilmenite, pp. 197.

REMARKS.—Students of the titanium minerals in sediments owe much to A. Brammall and H. F. Harwood for their exhaustive studies of these species, particularly brookite, which has always presented certain difficulties in unequivocal diagnosis. In the paper on "Dartmoor Detritals," the former author gives much information applicable to the identification of brookite under all conditions, together with some good illustrations of the Dartmoor types and their curious interference figures, the latter here reproduced in fig. 29.

¹ H. H. Thomas, *Q.J.G.S.*, lviii, 1902, p. 625, plate xxxii., fig. 6.

² H. H. Thomas, *Q.J.G.S.*, lxxv., 1909, p. 238.

³ P. G. H. Boswell, *Geol. Mag.*, lxi., 1924, p. 257.

⁴ P. G. H. Boswell, *Q.J.G.S.*, lxxix., 1923, p. 210.

⁵ P. G. H. Boswell, *Q.J.G.S.*, lxxix., 1923, p. 226.

⁶ H. B. Milner, *Q.J.G.S.*, lxxviii., 1922, pp. 362, 364-5.

⁷ I. S. Double, *Proc. Geol. Assoc.*, xxxv., 1924, p. 340.

⁸ A. Brammall, *Proc. Geol. Assoc.*, xxxix., 1928, pp. 31-34.

⁹ A. Brammall & H. F. Harwood, *Mineralogical Mag.*, xx., 1923, pp. 20-26.

NOTE ON THE INTERFERENCE FIGURE OF BROOKITE (DARTMOOR). (Quoted from A. Brammall, *Proc. Geol. Assoc.*, xxxix., 1928, pp. 33-4.)

"(a) Under the best conditions, the figure shows well-defined compound lemniscates approximating to arcs. In the 'straight' position it has the aspect

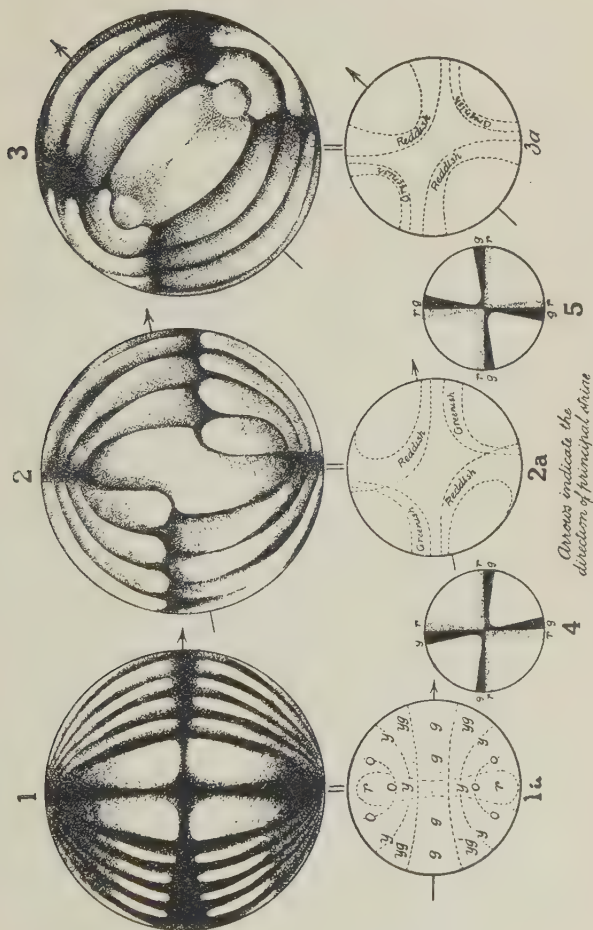


FIG. 29. Interference Figure of Brookite (Dartmoor).—A. Brammell.

of *fig. 1*, changing on rotation through 45° , to *fig. 2* and *fig. 3* in succession.

In *fig. 1* the N-S central bar is the more sharply defined and is flanked by reddish tints near the poles. The E-W bar is somewhat dispersed, the polar tints being dominantly greenish. The arc-like colour-bands are compounded of green and red, shading into yellow and orange in the inter-spaces. In each band, the red arc is more convex than the green, and the two overlap; the overlap segments are strikingly darker than the rest of the band.

- (b) Under less favourable conditions, the colour-bands shown in *figs. 1, 2* and *3* become indistinct or indiscernible: the colour-patterning shows an areal spread of tints (*fig. 1a*). On rotation through 45° *four* broad isogyral colour-bands evolve (*figs. 2a* and *3a*)—in place of the two sharply defined 'black' isogyres shown by normal biaxial figure. In each of the phases *1a, 2a* and *3a*, reddish tints dominate one pair of opposed quadrants; greenish tints dominate the other pair.
- (c) In the 'straight' position the figure shows the usual dark (neutral grey) cross. On the slightest rotation from this position each of the four arms of the cross becomes reddish on one side, greenish on the other (*figs. 4a* and *4b*). If rotation be continued through 45° , the green and red tints spread centrosymmetrically, in the manner shown in *figs. 2a* and *3a*."

CALCITE.

[Fig. 30. Pl. V.]

Chem. Comp. CaCO_3 .*System.* Rhombohedral.*Habit.* Highly varied and frequently complex. Commonly prismatic, rhombohedral, scalenohedral or twinned.*Structure.* Crystalline or massive.*Cleavage.* Perfect parallel to unit rhombohedron (10 $\bar{1}$ 1).Good parting parallel to (01 $\bar{1}$ 2) in twin crystals, more rarely parallel to (11 $\bar{2}$ 0).*Fracture.* Irregular, but rare.*Hardness.* Varies with composition, but usually about 3.*Spec. Grav.* 2.713 to 2.723.*Lustre.* Vitreous, pearly.*Colour.* Colourless, white or pale shades of yellow, red or brown due to impurity. Transparent to translucent.*Mag. Prop.* Non-magnetic.*Elect. Prop.* Bad conductor.*Opt. Prop.* R.I. low for ϵ , high for ω . $\omega = 1.65849$, $\epsilon = 1.48625$. Birefringence very high, $\omega - \epsilon = 0.17224$.Optically uniaxial, negative. (10 $\bar{1}$ 1) cleavage plates show partial interference figure. Straight extinction.*Characters in Sediments.* Usually occurs as highly irregular grains, slightly rounded. Twin striæ parallel to the major diagonals of the cleavage flakes (10 $\bar{1}$ 1) often observed. Diagnosed chiefly by the "twinkling" effect noted on rotation of polariser.*Occurrence.* In the Old Red Sandstone of the West Midlands;¹ in the Permo-Triassic rocks of the Midlands;² in the Lower Greensand of Kent and Surrey;³ in the Upper Greensand of Dorset;⁴ in Oligocene "glass" sand, Fontainebleau, Paris;⁵ in the dune sands of South Wales;⁶ in surface deposits of S.E. Devon;⁷ in shore sand, Kynance, Cornwall.⁸¹ W. F. Fleet, *Geol. Mag.*, lxiii., 1926, p. 512.² W. F. Fleet, *Proc. Geol. Assoc.*, xxxviii., 1927, p. 6.³ G. M. Davies, *Proc. Croydon Nat. Hist. Soc.*, 1915-16, p. 90.^{4, 5} Author's observations.⁶ A. Stuart, *Proc. Geol. Assoc.*, xxxv., 1924, p. 322.⁷ W. G. Shannon, *Geol. Mag.*, lxiv., 1927, pp. 145-153.⁸ Author's observations.

Possible Sources of Derivation. Chiefly from sedimentary rock masses, either as a primary or secondary constituent. Also from decomposition of lime-silicate minerals in igneous rocks. Recrystallized from shell-fragments.†

REMARKS.—Calcite very rarely occurs as simple rhombohedra in sediments; such forms are generally ascribable to dolomite. Identified chiefly by S.G., optical properties, and presence of twin lamellæ in many flakes; but where doubt remains, only chemical tests will settle the point, especially the distinction from dolomite. The principal tests are:—(1) Vigorous effervescence with cold HCl; dolomite effervesces slowly, if at all. Both minerals react readily to warm HCl. (2) With ferric chloride gives reddish-brown deposit of ferric hydroxide; dolomite only affected after prolonged treatment. (3) *Lemberg's Test*: 60 parts H₂O, 4 parts Al₂Cl₃ and 6 of logwood chips (*hæmatoxylon campechianum*) boiled together for 25 minutes; when cool treat mineral with this solution: calcite takes the stain after 5 to 10 minutes, dolomite remains unaltered. For other tests, see A. Holmes, *Petrographic Methods*, 1921, ch. vii.

† P. G. H. Boswell, *Geol. Mag.*, 1915, p. 255.

CASSITERITE. [Fig. 31. Pl. VI.]

Chem. Comp. SnO_2 .

System. Tetragonal.

Habit. Commonly euhedral. Bipyramidal, prismatic or twinned on (101).

Structure. Crystalline, massive, granular.

Cleavage. Imperfect parallel to (100), bad parallel to (111), trace parallel to (110).

Fracture. Subconchoidal, uneven.

Hardness. 6 to 7.

Spec. Grav. 6.8 to 7.1.

Lustre. Adamantine, submetallic or dull.

Colour. Brown, black, reddish-brown, more rarely pale yellow or greyish-white. Translucent to opaque.

Mag. Prop. Non-magnetic; rarely magnetic.

Elect. Prop. Moderate conductor.

Opt. Prop. R.I. high, $\omega = 1.9966$, $\epsilon = 2.0934$. Birefringence high, $\epsilon - \omega = 0.0968$. Optically uniaxial positive. Length slow. Interference figure often "splits" into pseudo-biaxial type in certain varieties: small axial angle. Interference colours frequently masked by natural colour. Often pleochroic: brown to yellow, yellow to grey, red-brown to pink or grey-green. Straight extinction of grain parallel to prism-edge.

Characters in Sediments. Commonly occurs as prismatic and pyramidal grains, or as irregular rolled crystals, either opaque with marked adamantine lustre, or of composite colour in which brown and red of different shades predominate. The colour is often distributed irregularly in the grain, giving a blotchy appearance; or some individuals may present small translucent patches in an otherwise opaque mass. Detrital, like alluvial, cassiterite is extremely variable in character, especially as regards its pleochroism, which is much more commonly developed than is generally realized. The scheme is broadly that of ϵ =brown-yellow to black, ω =golden yellow to grey, also changes from reddish-brown to pink or to a peculiar greenish-grey tinge (resembling certain types of hypersthene). Inclusions in translucent varieties are common and are

nearly always iron oxide. Zoning is frequent and some very beautiful examples of colour-band patterning are met with. Knee-shaped twins, characteristic of many alluvial occurrences, are rare as detrital grains. Well marked fluting or finer striae parallel to the principal axis are commonly noted in prismatic grains, while striae parallel to pyramidal faces occur (Dartmoor).

Occurrence. In the New Red Sandstone of the West of England;¹ in the Bunter Pebble Bed of the West of England;² in the Greensand, Eocene, Oligocene and Pliocene deposits of the West of England;³ in the Pliocene deposits of Cornwall;⁴ in the dune sands of South Wales;⁵ in Dartmoor detritals;⁶ in Clay-with-Flints, Walton Heath, Surrey.⁷

Possible Sources of Derivation. From veins, pegmatites, etc., associated with granitic rocks; from metalliferous lodes. Rarely a minor accessory species in granite itself.

REMARKS.—Cassiterite as a constituent of detrital sediments is probably more common than existing records suggest, but is liable to be confused with rutile, hypersthene, titanite, or other "dusky" brown minerals. Microscopical diagnosis is by no means always unequivocal and the simple zinc and HCl test should always be resorted to wherever possible. This consists of the use of a metallic zinc bath in which the supposed cassiterite grains are placed, then covered with dilute HCl; the nascent hydrogen evolved results in an aluminium-grey coating to the tinstone, which can be easily detected under the microscope, and is positive.

¹ H. H. Thomas, *Q.J.G.S.*, lxxv., 1909, p. 231.

² H. H. Thomas, *Q.J.G.S.*, lviii., 1902, p. 623.

³ P. G. H. Boswell, *Q.J.G.S.*, lxxix., 1923, p. 226.

⁴ H. B. Milner, *Q.J.G.S.*, lxxviii., 1922, pp. 359, 364.

⁵ A. Stuart, *Proc. Geol. Assoc.*, xxxv., 1924, p. 321.

⁶ A. Brammall, *Proc. Geol. Assoc.*, xxxix., 1928, pp. 36-37 and plate 2.

⁷ G. M. Davies, *Proc. Croydon Nat. Hist. Soc.*, 1915-16, p. 89.

General References.

P. G. H. Boswell, "The Rarer Detrital Minerals of British Sedimentary Rocks," *Trans. Geol. Soc. Glasgow*, xviii., 1926-27, p. 135.

C. Raeburn & H. B. Milner, "Alluvial Prospecting," 1927, pp. 362-364 (for full description of alluvial occurrences).



FIG. 31. CASSITERITE.

Typical Crystals and Fragments from Dartmoor. (From Brush-drawings by A. Brammall.) Grade-size up to 8 mm.

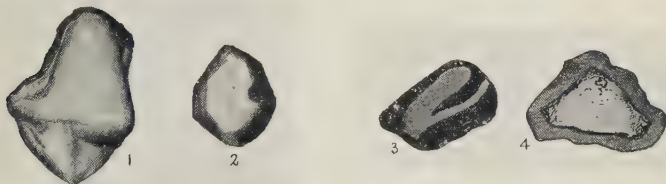


FIG. 32. CEYLONITE.

1, 2. Alluvials, Gold Coast, W. Africa. [x 15.] 3. Pliocene, S. of Elham, Folkestone. [x 30.] 4. From Monazite Sand, Travancore, India. [x 25.]



FIG. 33. CHIASTOLITE.

Pleistocene Gravel,
Bayford, Herts. [x 40.]

3. Shooters Hill Gravel,
London. [x 40.]

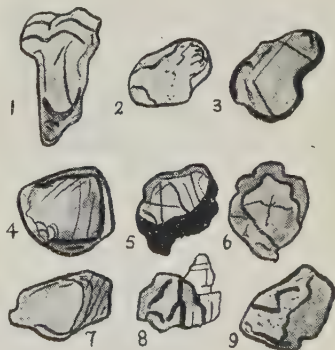


FIG. 34. CHLORITE.

1-9. Shore Sand, Lizard District,
Cornwall. (1, 5, 6 & 8 with pro-
nounced cleavage.) [All x 12.]

CELESTITE.

Chem. Comp. SrSO_4 .

System. Orthorhombic.

Habit. Tabular parallel to (001); prismatic; less commonly pyramidal.

Structure. Crystalline, fibrous, radiating.

Cleavage. Perfect parallel to (001), good parallel to (110), imperfect parallel to (010).

Fracture. Irregular, distinct.

Hardness. 3 to 3.5.

Spec. Grav. 3.95 to 3.97.

Lustre. Vitreous.

Colour. Colourless, white, pale blue, rarely pink.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. high, $\alpha = 1.622$, $\beta = 1.624$, $\gamma = 1.631$. Birefringence low, $\gamma - \alpha = 0.009$. Optically biaxial positive. $Bxa = Z$ normal to (100). Optic axial plane parallel to (010). $X \parallel c$, $Z \parallel a$. $2V = 51^\circ$. Straight extinction parallel to prism-edge or principal axis. Non-pleochroic. Dispersion, $\rho < \nu$.

Characters in Sediments. Celestite, like barite and anhydrite, is almost invariably authigenic, associated with limestone, certain sandstones in which it occurs as a cementing medium, marls, gypsum and rock-salt. Consequently when isolated as detached flakes it tends to be of fantastic shape, *i.e.*, the shape of the original interstice which it filled. There is little available on microscopical evidence *alone* to determine definitely this species, which is liable to confusion with related sulphates and with other colourless minerals. Since, when it does occur, it is usually prolific, little difficulty is experienced in applying the customary flame-test (crimson) or spectroscopic methods of discrimination.¹

Occurrence. In the New Red Sandstone of the West of England;¹ in the Triassic gypseous deposits and dolomites near Jena;² in Triassic sandstones and marls of Yate, Gloucestershire.³

Possible Sources of Derivation. From cementing (authigenic) media in calcareous and arenaceous rocks; from geodes and secondary masses in marls; from veins and metalliferous bodies.

¹ H. H. Thomas, *Q.J.G.S.*, lxxv., 1909, p. 234.

² E. Kalkowsky, *Zeitschr. deutsch. geol. Gesellsch.*, lxxiii., 1922, pp. 1-23.

³ Well-known locality.

CEYLONITE (Pleonaste). [Fig. 32. Pl. VI.]

VARIETY OF SPINEL.

Chem. Comp. (Mg,Fe)O.Al₂O₃.

System. Cubic.

Habit. Octahedral, sometimes with dodecahedral development.

Structure. Crystalline.

Cleavage. Imperfect parallel to (111).

Fracture. Conchoidal.

Hardness. 8.

Spec. Grav. 3.5 to 3.6.

Lustre. Vitreous; splendid to dull.

Colour. Green, blue-green.

Mag. Prop. Weakly magnetic.

Elect. Prop. Bad conductor.

Opt. Prop. R.I. high, 1.7135 to 1.7200, varying with composition and depth of colour. Isotropic.

Characters in Sediments. Usually exhibits some degree of rounding, but the simple octahedral habit is very characteristic, and is, in fact, one of the chief diagnostic properties of this mineral in detrital sediments. It is sometimes highly fractured when it may resemble green garnet, a mineral of similar refractive index; green garnet (vars. Uvarovite, Andradite or Demantoid) often exhibits anomalous polarisation colours, very rare with ceylonite. This mineral seldom has inclusions, green garnet is liable to show them.

Occurrence. Possibly in the Lower Keuper Sandstone of the English Midlands;¹ rarely in the Sands of the Upper Lias—Inferior Oolite of the West of England;² in the Thanet Beds of the London Basin;³ in the Bagshot Beds of Essex;⁴ in the Norwich Crag (newer Pliocene) of the East of England;⁵ in the Lenham

¹ W. F. Fleet, *Geol. Mag.*, lxii., 1925, p. 124.

² P. G. H. Boswell, *Geol. Mag.*, lxi., 1924, p. 257.

³ P. G. H. Boswell, *Q.J.G.S.*, lxxi., 1915, table IV.

⁴ S. W. Wooldridge, *Proc. Geol. Assoc.*, xxxv., 1924, p. 377.

⁵ I. S. Double, *Proc. Geol. Assoc.*, xxxv., 1924, p. 338.

(Pliocene) Beds of Sanderstead, Surrey;¹ occasionally in the shore sands of East England and Brittany;² in Dartmoor detritals.³

Possible Sources of Derivation. Basic and ultrabasic igneous rocks; metamorphosed limestone, dolomite and argillaceous rocks; aurcole and xenolithic hornfels containing corundum, cordierite, etc.

REMARKS.—An infrequent species, though it seems to be a constant constituent of the Lenham Beds; probably often confused with garnet and possibly certain varieties of chlorite; see under Spinel (p. 238) for possible method of distinction from the former mineral.

¹ F. Gossling & S. W. Wooldridge, *Proc. Geol. Assoc.*, xxxvii., 1926, p. 99.

² Observations of F. T. Ingham and the author.

³ A. Brammall, *Proc. Geol. Assoc.*, xxxix., 1928, p. 47.

General Reference.

P. G. H. Boswell, "The Rarer Detrital Minerals of British Sedimentary Rocks," *Trans. Geol. Soc. Glasgow*, xviii., 1926-27, p. 135.

CHALCEDONY AND CHERT.

Chem. Comp. SiO_2 .

System. Doubtful.

Habit. Botryoidal, massive, compact.

Structure. Cryptocrystalline.

Cleavage. None.

Fracture. Conchoidal, irregular, splintery.

Hardness. 7.

Spec. Grav. 2.59 to 2.64.

Lustre. Resinous, dull.

Colour. Pale shades of blue, bluish-white, red, black or mottled. Translucent to opaque.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. low, mean R.I. 1.537 (Canada balsam 1.55). Birefringence low. Often exhibits aggregate polarisation. Fibrous forms extinguish parallel to their length.

Characters in Sediments. Grains usually sharply angular and much fractured. Clear, colourless, often void of all inclusions. With polarised light little change is noted, homogeneity of colour and appearance being due to the cryptocrystalline structure. Chert grains frequently occur as conspicuous constituents of detrital sediments; such grains may preserve traces of organic structure, or they may be associated with pellets of pyrite. Chalcedony itself is diagnosed from its presence in the light crop, its contrasted appearance with quartz (which has an appreciably higher R.I.), its frequent failure to extinguish in any position, and its dull lustre (compared with quartz). Chert exhibits characteristic aggregate polarisation and is far more varied in character (inclusions, iron-staining, etc.) than pure chalcedony.

Occurrence. Chalcedony and chert in the Upper Lias—Inferior Oolite sands of the West of England;¹ chert in the Cretaceous and Tertiary rocks of the West of England;² flint and chert in the Cretaceous rocks of the

¹ P. G. H. Boswell, *Geol. Mag.*, lxi., 1924, p. 252.

² P. G. H. Boswell, *Q.J.G.S.*, lxxix., 1923, p. 226.

Croydon Regional Survey Area, Surrey;¹ in the Middle Chalk, Beer Head, S.E. Devon;² chert in the dune sands of South Wales.³

Possible Sources of Derivation. Chalcedony is ubiquitous in igneous, metamorphic and sedimentary rocks; commonly formed as a secondary deposit in cavities as a result of infiltration of silica-bearing solutions; organic deposits (especially flint and chert).

¹ G. M. Davies, *Proc. Croydon Nat. Hist. Soc.*, 1915-16, p. 87.

² W. F. Hume, "Cretaceous Rocks of Britain," *Mem. Geol. Surv.*, ii., 1903, pp. 509, 513.

³ A. Stuart, *Proc. Geol. Assoc.*, xxxv., 1924, p. 325.

CHIASTOLITE. [Fig. 33. Pl. VI.]

VARIETY OF ANDALUSITE.

Chief mineralogical properties as for Andalusite (q.v.).

Characters in Sediments. Where graphitic or carbonaceous inclusions are concentrated within the mineral grain so as to exhibit a tessellated or geometrical design, *e.g.*, a black cross, the variety "chiastolite" is diagnosed. There is, however, some difference of opinion among petrographers as to what should and what should not be called "chiastolite," since every gradation is met with in detrital sediments from colourless andalusite with a few irregularly scattered carbonaceous inclusions, to those grains in which the black cross is definite. I. S. Double states, "The quantity and the mode of arrangement of the black inclusions is very variable. When part or all of the black cross associated with the varietal characters of chiastolite has been seen, that mineral is recorded."⁴ Although this only applies to a specific instance (late Tertiary deposits of the East of England), it is, in the author's opinion, the correct interpretation in all circumstances, and where the inclusions are disseminated quite arbitrarily in the grains, these are better recorded as andalusite. On the whole, definite grains of chiastolite seldom show pleochroism so characteristic of many occurrences of andalusite, and grains preserving the complete black cross are uncommon. Double illustrates four types of chiastolite in his paper; Prof. Boswell also figures two examples from the Oligocene beds of Devonshire. Detrital chiastolite is more often than not irregular in form, though occasionally the orthorhombic prism is preserved, when the grain exhibits straight extinction.

Occurrence. In the Sands of the Upper Lias—Lower Inferior Oolite of the West of England(?);¹ in the Oligocene Beds of the Bovey Basin, Devonshire;² in the gravels of doubtful age at Riddaford Water, Bovey,

¹ P. G. H. Boswell, *Geol. Mag.*, lxi., 1924, p. 258.

² P. G. H. Boswell, *Q.J.G.S.*, lxxix., 1923, pp. 218, 220.

Devonshire;¹ in the Red Crag and Coralline Crag (Pliocene) of the East of England;² in the Lenham Beds of Sanderstead, Surrey,³ and of the Folkestone district;⁴ in the matrix of the Pebble Gravel of the Hertfordshire plateau.⁵

Possible Sources of Derivation. Metamorphosed argillaceous rocks, *e.g.*, chistolite slate.

¹ *Ibid.*, p. 223.

² I. S. Double, *Proc. Geol. Assoc.*, xxxv., 1924, pp. 337, 339.

³ F. Gossling & S. W. Wooldridge, *Proc. Geol. Assoc.*, xxxvii., 1926, p. 98.

⁴ Author's observations.

⁵ S. W. Wooldridge & D. M. C. Gill, *Proc. Geol. Assoc.*, xxxvi., 1925, p. 171.

CHLORITE. [Fig. 34, Pl. VI.]

Chem. Comp. Ill-defined family of micaceous minerals frequently representing alteration products of amphiboles and micas. Essentially silicates of aluminium, ferrous iron, magnesium and hydroxyl, the two chief crystalline varieties being Penninite and Clinochlore.

System. Monoclinic (pseudo-rhombohedral symmetry in Penninite).

Habit. Pseudo-hexagonal plates with bevelled edges; tabular, with prominent basal plane.

Structure. Foliated, massive. Rarely crystalline.

Cleavage. Perfect basal parallel to (001).

Fracture. Irregular.

Hardness. 2 to 2.5.

Spec. Grav. 2.65 to 3. (Varies with composition).

Lustre. Vitreous, (001) pearly.

Colour. Shades of green, more rarely pale greenish-yellow.

Transparent to translucent.

Mag. Prop. Weakly magnetic.

Elect. Prop. Poor conductor.

Opt. Prop. R.I. low, $a = 1.585$, $\beta = 1.588$, $\gamma = 1.596$ (Clinochlore); $a = 1.576$, $\gamma = 1.579$ (Penninite). Birefringence moderate in Clinochlore, $\gamma - a = 0.011$; low in Penninite, $\gamma - a = 0.003$. $Bxa = Z$ or X . Different varieties may show biaxial interference figures, and may be either positive or negative, while the great variation in the optic axial angle occasions the pseudo-uniaxial appearance of Penninite, where $2V$ may be 0° . Pleochroism noticed in some varieties, especially those of deep colour: dark green to yellowish-green.

Characters in Sediments. It is very rarely that either Penninite or Clinochlore are specifically determinable in detrital sediments. Usually the recorded "chlorite" is a complex decomposition product after amphiboles, pyroxenes or micas, and betrays its presence by its grass-green colour (yellow-green by reflected light), somewhat laminated or micaceous habit, refractoriness to most optical tests, and low, almost ultra-blue polarisation tints; or often completely isotropic. In form it is commonly subangular and void of crystal outline.

Inclusions are very common, mostly iron-ores. Striae sometimes noted across the grains in indefinite directions; these are frequently "wavy." Cleavage flakes, in general appearance somewhat resembling mica, may exhibit interference figures which materially aid identification.

Occurrence. In the Cambrian, Devonian, Carboniferous and Permo-Triassic rocks of the English Midlands;¹ in the Old Red Sandstone of the West Midlands;² in the New Red Sandstone of the West of England;³ in the Upper Lias—Lower Inferior Oolite of the West of England;⁴ in the Northampton Ironstone;⁵ in the Pliocene sands of West Cornwall;⁶ in the later Tertiary deposits of the East of England;⁷ in the dune sands of South Wales.⁸

Possible Sources of Derivation. From slates, phyllites and similar metamorphic rocks.

REMARKS.—The so-called "chlorite" derived from relaxed basic igneous rocks (more particularly their ferro-magnesian constituents), is poorly individualized as crystal and certainly rare as either penninite or clinochlore. In such cases it is better designated as "chloritic matter" implying considerable variation in composition according to precise nature of parent species and destabilising environment.

¹ W. F. Fleet, *Geol. Mag.*, lxii., 1925, pp. 98-128 (p. 126).

² W. F. Fleet, *Geol. Mag.*, lxiii., 1926, pp. 505-516 (p. 513).

³ H. H. Thomas, *Q.J.G.S.*, lxv., 1909, p. 239.

⁴ P. G. H. Boswell, *Geol. Mag.*, lxi., 1924, p. 256.

⁵ J. G. A. Skerl, *Proc. Geol. Assoc.*, xxxviii., 1927, p. 382.

⁶ H. B. Milner, *Q.J.G.S.*, lxxviii., 1922, pp. 357, 362, 365.

⁷ I. S. Double, *Proc. Geol. Assoc.*, xxxv., 1924, p. 342.

⁸ A. Stuart, *Proc. Geol. Assoc.*, xxxv., 1924, p. 324.

CHLORITOID—OTTRELITE. [Fig. 35. Pl. VII.]

Chem. Comp. Chloritoid, $H_2(Fe,Mg).Al_2SiO_7$.

Ottrelite, $H_2(Fe,Mn).Al_2Si_2O_9.(?)$

System. Monoclinic or Triclinic. (?)

Habit. Similar to mica, but rounded or elliptical forms most common; rarely tabular with hexagonal outline; occasionally rhombic.

Structure. Crystalline, radiating aggregates; sometimes curved; scaly.

Cleavage. Good parallel to (001). In chloritoid there is an imperfect cleavage parallel to (443) inclined about 90° to (001) and about 60° to one another (Iddings); also parallel to (010).

Fracture. Irregular, both species brittle.

Hardness. 6 to 7.

Spec. Grav. 3.52 to 3.57, chloritoid; 3.3 ottrelite.

Lustre. Pearly, especially on cleavage flakes.

Colour. Shades of dark green to greenish-black; sometimes green to indigo-blue.

Mag. Prop. Weakly magnetic.

Elect. Prop. Bad conductor.

Opt. Prop. R.I. high, mean 1.710 to 1.75. Birefringence low, $\gamma - a = 0.007$ to 0.016. Optically biaxial, positive. Optic axial plane parallel to (010). $Bxa = Z$ inclined at 12° to the normal to (001) [Tschermak]. $X \parallel b$. $2V = 36^\circ - 60^\circ$ (chloritoid), variable in ottrelite. Dispersion of bisectrices strong, $\rho > v$. Pleochroism strong to moderate in chloritoid: $Z =$ yellow-green or colourless, $Y =$ indigo-blue, $X =$ olive green.

Characters in Sediments. Detrital chloritoid is not a common mineral, but it has been definitely determined in a few instances in British sediments (see below); detrital ottrelite *per se* has not yet been recorded, and it is doubtful whether it is sufficiently stable to survive transport to sedimentary accumulations. Prof. P. G. H. Boswell has described the characters of chloritoid in some detail: “. . . as scaly flakes . . . or wisps . . . often consisting of several flakes partly superposed. A second cleavage at about 90 degrees to the almost perfect basal cleavage is sometimes seen running across the flakes, and a third cleavage occurs at

about 70 degrees to the second cleavage. . . . Average refractive index for sodium light . . . is >1.710 and <1.715 , but is nearer the former value. . . . Pleochroism distinctive . . . absorption being moderately strong. The scheme is, parallel to X (that is, approximately, second cleavage) dirty green or olive-coloured, parallel to Y indigo to smoky-blue. The wisps show less well-marked changes of colour. The birefringence is usually very low, ultra-blues, ultra-browns and indigo tints . . . occasionally first order greys and yellows are seen. Most of the flakes give a biaxial figure, the emergence of the acute bisectrix being almost central. The sign is positive, and the isogyres frequently show well-marked dispersion. The wisps show straight extinction on the length."¹ Chloritoid from the shore sands of Brittany, observed by the author, is identified chiefly by its blue or bluish-green colour, high refractive index, low birefringence, strong pleochroism and dispersion of the optic axes, interference figure and sign, in all of which properties it agrees closely with the foregoing data. It tends to be scaly, showing a delicate, laminated structure, the "wisp" varieties being less common. In very small grains, its diagnosis is by no means always certain.

Occurrence. In sands of the Upper Lias—Lower Inferior Oolite of the West of England;¹ in the Northamptonshire Ironstone;² in the Upper Kimmeridge Clay and Portland Sand of Dorset, Wiltshire, Oxfordshire and Buckinghamshire;³ from beds of sand and clay sampled from two borings in the plain of Lombardy, northern Italy;⁴ in shore sands from various localities in southern Brittany.⁵

Possible Sources of Derivation. Crystalline schists, phyllites and quartzites. From reconstituted argillaceous sediments.

¹ P. G. H. Boswell, *Geol. Mag.*, lxi., 1924, pp. 254-256.

² J. G. A. Skerl, *Proc. Geol. Assoc.*, xxxviii., 1927, p. 382.

³ E. Neaverson, *Proc. Geol. Assoc.*, xxxvi., 1925, p. 250.

⁴ I. Chelussi, *Boll. Soc. geol. ital.*, xliii., 1924, pp. 161-169.

⁵ Observations of F. T. Ingham and the author.

General Reference.

P. G. H. Boswell, "The Rarer Detrital Minerals of British Sedimentary Rocks," *Trans. Geol. Soc. Glasgow*, xviii., 1926-27, pp. 138-9.

CHROMITE.

Chem. Comp. $\text{FeO.Cr}_2\text{O}_3$.

System. Cubic.

Habit. Octahedral or combination of octahedron and dodecahedron.

Structure. Rarely crystalline, commonly massive.

Cleavage. None.

Fracture. Uneven.

Hardness. 5.5.

Spec. Grav. 4.32 to 4.57.

Lustre. Metallic to submetallic, rarely dull.

Colour. Black or brownish-black, frequently with purple tarnish.

Mag. Prop. Moderately magnetic.

Elect. Prop. Good conductor.

Opt. Prop. Opaque in transmitted light, except in very thin section, when the deep brown colour and isotropic character are apparent. R.I. high, $n=2.0695$.

Characters in Sediments. Occurs as rounded octahedral grains or as subangular and irregular fragments. Deposits derived from ultrabasic rocks often contain a high percentage of this mineral, which is identified chiefly by its submetallic lustre in reflected light, and by its colour and form. Locally in alluvial sands suitably derived.

Occurrence. In the Middle Chalk of Beer Head, S.E. Devon;¹ ? in the dune sands of South Wales;² in shore sands of Kynance Cove, Coverack, etc., Lizard district, Cornwall.³

Possible Sources of Derivation. Chiefly from peridotites, serpentines and associated ultrabasic rocks; more rarely from crystalline schists.

REMARKS.—The microscopical determination of chromite is not always convincing, and, if possible, should be supplemented by chemical test. (With borax bead, chromium yields green colour in both oxidising and reducing flames).

¹ G. M. Davies, *Geol. Mag.*, 1919, pp. 506-7.

² A. Stuart, *Proc. Geol. Assoc.*, xxxv., 1924, p. 321.

³ Author's observations.

General References.

C. Raeburn & H. B. Milner, "Alluvial Prospecting," 1927, p. 367 and references cited (for alluvial chromite).

P. G. H. Boswell, *Proc. Liverpool Geol. Soc.*, xiii., 1923, p. 273. (Record of chromite from sediments obtained on the "Challenger" Expedition).

CORDIERITE.

Chem. Comp. $4(\text{MgFe})\text{O} \cdot 4(\text{Al}_2\text{O}_3) \cdot 10\text{SiO}_2 \cdot \text{H}_2\text{O}$.

System. Orthorhombic.

Habit. Euhedral prismatic crystals; often twinned; sometimes complex.

Structure. Crystalline, granular.

Cleavage. Good parallel to (010), poor parallel to (100) and (001).

Fracture. Subconchoidal.

Hardness. 7 to 7.5.

Spec. Grav. 2.60 to 2.66.

Lustre. Vitreous.

Colour. Shades of blue or yellowish-grey.

Mag. Prop. Moderately magnetic.

Elect. Prop. Poor conductor.

Opt. Prop. R.I. low, $\alpha = 1.532$, $\beta = 1.536$, $\gamma = 1.539$.

Birefringence low, $\gamma - \alpha = 0.007$. Optically biaxial, negative. Optic axial plane parallel to (100). $Bxa = X \parallel c$ normal to (001). $Y \parallel a$, $Z \parallel b$. Optic axial angle variable, $2V = 40^\circ$ to 84° . $Y > Z > X$. Usually pleochroic: $Y = \text{dark blue}$, $Z = \text{light blue}$, $X = \text{yellowish-white}$. Straight extinction parallel to prism-edge. Weak dispersion, $\rho < \nu$.

Characters in Sediments. Generally occurs as small sub-angular grains, almost colourless, weakly pleochroic and birefringent. Minute and opaque inclusions are common; these may be surrounded by pleochroic haloes; Brammell records zircon, monazite, quartz, feldspars, biotite, white mica, rutile needles, granules of green spinel and black opaque matter. In its unaltered form it is of rare occurrence in sediments, Pinite being the usual product met with. Pinite is recognized by its green or greenish-brown colour, micaceous habit and its tendency to form cryptocrystalline aggregates. On the subject of alteration products of cordierite, and its instability in detrital sediments, see paper by Brammell. (Ref. ², p. 163).

Occurrence. ? in the New Red Sandstone of the West of England;¹ in Dartmoor detritals.²

Possible Sources of Derivation. Crystalline schists and gneisses, less commonly from acid igneous rocks.

REMARKS.—Cordierite being of low specific gravity will occur in the light concentrate, and may thus be easily confused with quartz, or overlooked altogether. It is distinguished from the latter by its biaxial interference figure and by its pleochroism, if developed, and may be conveniently separated from quartz and felspar by the electro-magnet. For a full and valuable discussion of cordierite in the Dartmoor detritals (much of which is applicable to other occurrences) see reference ² below.

¹ H. H. Thomas, *Q.J.G.S.*, lxx, 1909, p. 234.

² A. Brammall, *Proc. Geol. Assoc.*, xxxix., 1928, pp. 40-43.

CORUNDUM. [Fig. 36. Pl. VII.]

Chem. Comp. Al_2O_3 .

System. Rhombohedral.

Habit. Hexagonal bipyramidal. Rounded crystals.

Structure. Granular.

Cleavage. Parallel to (0001), but rarely seen in small grains. Both basal and rhombohedral partings occur.

Fracture. Conchoidal, uneven.

Hardness. 9.

Spec. Grav. 3.95 to 4.10.

Lustre. Adamantine, vitreous.

Colour. Frequently colourless, or shades of blue (Sapphire), red (Ruby), or yellowish-brown.

Mag. Prop. Non-magnetic.

Elect. Prop. Bad conductor.

Opt. Prop. R.I. high, $\epsilon = 1.7598$, $\omega = 1.7690$.

Birefringence low, $\omega - \epsilon = 0.0092$. Optically uniaxial, negative. Length fast. Straight extinction. Strongly coloured varieties are pleochroic, particularly sapphire: ϵ blue to ω bluish-green.

Characters in Sediments. Grains usually exhibit fracture and irregular outline. Less common are the basal flakes, determined by parting, yielding good uniaxial figure. The colour is often unevenly distributed in the grains, some appearing very "blotchy." Anomalous optical properties are sometimes noted which are probably due to twinning, e.g., pseudo-biaxial figure with $2V = \pm 50^\circ$.

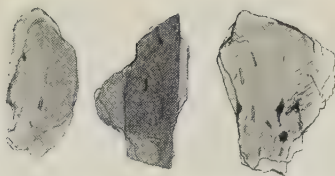
Occurrence. In the Pennant Sandstones, South Wales;¹ in the Kimmeridgian-Portlandian Sands, Bucks, etc.;² in the Ashdown Sand (Wealden), Hastings, Sussex;³ in the Sandgate Beds, Tilburstow Hill, Surrey;⁴ in the Greensand and Eocene deposits of the Haldon Hills,

¹ A. Heard, *Geol. Mag.*, lx., 1923, p. 83 *et seq.*

² E. Neaverson, *Proc. Geol. Assoc.*, xxxvi., 1925, p. 240 *et seq.*

³ H. B. Milner, *Proc. Geol. Assoc.*, xxxvi., 1925, p. 315.

⁴ G. M. Davies, *Proc. Croydon Nat. Hist. Soc.*, 1915-16, p. 89.



1 2 3
FIG. 35. CHLORITOID.

1. Shore Sand, Dinard, Brittany. [x 45.] 2, 3. Recent Sand, Le Pouldu, Brittany. [x 45.]

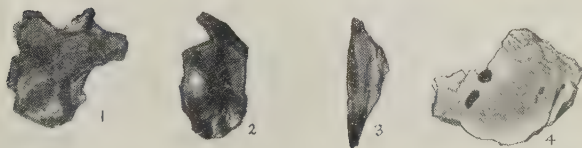


FIG. 36. CORUNDUM.

- 1, 3, 4. Pliocene Sand, St. Keverne, Cornwall. [1, 3, x 60.] [4, x 55.]
2. Miocene Sand, Los Angeles, Calif., U.S.A. [x 50.]

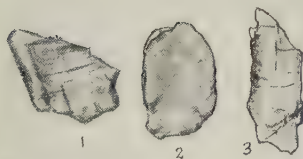


FIG. 37. DIOPSIDE.

1. Miocene Sand, Santa Fe Springs, Calif., U.S.A. [x 45.]
2. Shore Sand, Kynance Cove, Cornwall. [x 45.]
3. do. Speeton, Yorks. [x 45.]

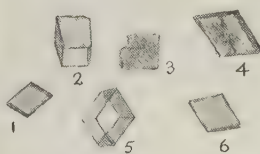


FIG. 38. DOLOMITE.

- 1-6. "Portland Sand," Dorset. [x 40.]

Devon;¹ in the Pliocene of West Cornwall; in deposits of doubtful age at Marazion, Cornwall;² in surface deposits of S.E. Devon;³ in Dartmoor detritals;⁴ in sea-bottom deposits of the Gulf of Manaar.⁵

Possible Sources of Derivation. Igneous or metamorphic rocks, especially contact-metamorphosed limestones. Alluvial deposits.

REMARKS.—The combination of a high R.I., blotchy colouring (where developed) and low birefringence aids identification. Of sporadic occurrence in detrital sediments; colourless or yellow varieties are the most common, sapphire on the whole rare, ruby not so far recorded (detrital), according to the author's observations.

¹ P. G. H. Boswell, *Q.J.G.S.*, lxxix., 1923, pp. 216, 226.

² P. G. H. Boswell, *Q.J.G.S.*, lxxix., 1923, p. 226.

³ W. G. Shannon, *Geol. Mag.*, lxiv., 1927, p. 147.

⁴ A. Brammall, *Proc. Geol. Assoc.*, xxxix., 1928, p. 44.

⁵ J. Lomas, in W. H. Herdman, "Rep. on Pearl Oyster Fisheries of the Gulf of Manaar," *Roy. Soc.*, 1903.

General References.

P. G. H. Boswell, "The Rarer Detrital Minerals of British Sedimentary Rocks," *Trans. Geol. Soc. Glasgow*, xviii., 1926-27, p. 136.

C. Raeburn & H. B. Milner, "Alluvial Prospecting," 1927, pp. 375-377 (for alluvial corundum).

DIOPSIDE. [Fig. 37. Pl. VII.]

Chem. Comp. $\text{Ca}(\text{Mg}, \text{Fe})(\text{SiO}_3)_2$.

System. Monoclinic.

Habit. Prismatic, more rarely tabular or bladed; sometimes twinned about (100).

Structure. Crystalline.

Cleavage. Frequent parallel to (110); sometimes parallel to (100), rarely parallel to (010). Parting parallel to (001) in twinned crystals.

Fracture. Uneven: often shown by irregular cracks traversing the crystal.

Hardness. 5 to 6.

Spec. Grav. 3.11 to 3.42.

Lustre. Vitreous, sometimes resinous.

Colour. Colourless, pale green, white or grey.

Mag. Prop. Weakly magnetic.

Elect. Prop. Moderate conductor.

Opt. Prop. R.I. high, $\alpha = 1.6710$, $\beta = 1.6780$, $\gamma = 1.7000$. Birefringence high, $\gamma - \alpha = 0.0290$. Optically biaxial, positive. $2V = 58^\circ 43'$. Optic axial plane parallel to (010). $Bxa = Z$ inclined at $38^\circ 30'$ to c axis (varies). Oblique extinction: angle 38° to 45° (measured from c in the plane (010)). $Y \parallel b$. Tabular grains parallel to (100) give straight extinction parallel to first cleavage. Slight dispersion of bisectrices: $\rho > \nu$. Non-pleochroic.

Characters in Sediments. Detrital diopside is distinguished chiefly by its tendency to occur in colourless to grey or pale green grains, by its refractive index, high polarisation colours and extinction angle (higher than kyanite, with which, in the absence of cleavage traces in that mineral, it is liable to confusion). Incipient alteration to serpentine, calcite and epidote may sometimes be noted. Inclusions of ilmenite, magnetite and apatite are not uncommon.

Occurrence. In the dune sands of South Wales;¹ in the wind-blown sands of Pembrokeshire (Newgale);² in the shore sands of the Lizard, Cornwall;² sands and clays sampled from two borings in the plain of Lombardy, northern Italy;³ various foreign Tertiary sands rich in pyroxene minerals.²

¹ A. Stuart, *Proc. Geol. Assoc.*, xxxv., 1924, p. 324.

² Author's observations.

³ I. Chelussi, *Boll. Soc. geol. ital.*, xliii., 1924, pp. 161-169

Possible Sources of Derivation. Igneous rocks, especially of a basic type. Gneisses, schists and contact metamorphic rocks.

REMARKS.—The optical properties of the monoclinic pyroxenes vary considerably with chemical composition, especially with the amount of iron present. *Diallage*, a variety of augite-diopside, may sometimes be noted in recent sands derived from diallage-bearing rocks, *e.g.*, gabbro, Lizard, Cornwall; it is recognized by its platy character, irregular outline, bronze-like lustre and inclusions. It must not be confused with bronzite (enstatite) the orthorhombic pyroxene (p. 173).

DOLOMITE [Fig. 38. Pl. VII.]

Chem. Comp. (Ca,Mg)CO₃.

System. Rhombohedral (Trigonal).

Habit. Simple rhombohedron (10 $\bar{1}$ 1) or irregular. Twinned about (011 $\bar{2}$).

Structure. Crystalline or massive.

Cleavage. Very perfect parallel to unit rhombohedron (10 $\bar{1}$ 1). Parting parallel to (011 $\bar{2}$).

Fracture. Conchoidal, but seldom observed.

Hardness. 3.5 to 4.

Spec. Grav. 2.8 to 2.9.

Lustre. Vitreous, pearly.

Colour. Colourless, white, greenish-white, brown and reddish-brown. Transparent to translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Bad conductor.

Opt. Prop. R.I. low for ϵ , high for ω . $\omega = 1.68174$, $\epsilon = 1.50256$, both ω and ϵ vary with amount of FeCO₃ present. (See Iddings, *Rock Minerals*, 1906, p. 469). Birefringence high, $\omega - \epsilon = 0.17918$. Optically uniaxial, negative. Usually shows a partial figure. Non-pleochroic.

Characters in Sediments. Chiefly recognized by its simple rhombohedral habit (rare in calcite), characteristic "twinkling" (on rotation of polariser) and sometimes by its zoning; almost invariably of secondary origin, hence tends to exhibit its rhombohedral character conspicuously. In some instances the iron-bearing dolomite, *Ankerite* (CaCO₃(Mg,Fe)CO₃) is suggested by the reddish-brown variety observed in certain sediments; this variety has a slightly higher gravity, 2.95 to 3.1.

Occurrence. In Devonian limestones, Torquay district;¹ in the Keuper Marls of Charnwood, Leicestershire;² in the Portland Sand of Dorset;³ in the North Sea Drift (from Overstrand to Heydon), Norfolk;⁴ in the dune sands of South Wales.⁵

¹ W. G. Shannon, *Proc. Geol. Assoc.*, xxxix., 1928, p. 150.

² T. O. Bosworth, "Keuper Marls Around Charnwood," Leicestershire, *Leicester Lit. & Phil. Soc.*, ch. xii., p. 81, *et seq.* Also C. G. Cullis, Rept. Brit. Assoc. for Adv. of Sci., Leicester, 1907, p. 506.

³ M. P. Latter, *Proc. Geol. Assoc.*, xxxvii., 1926, p. 85.

⁴ P. G. H. Boswell, *Proc. Geol. Assoc.*, xxvii., 1916, p. 92.

⁵ A. Stuart, *Proc. Geol. Assoc.*, xxxv., 1924, p. 322.

Possible Sources of Derivation. Derived dolomite is very rare, but if present is probably traceable to dolomitic limestone close at hand; in sediments is generally authigenic.

REMARKS.—Owing to its higher gravity than calcite, dolomite tends to come down with the “heavy” crop separated with bromoform. It is practically insoluble in cold hydrochloric acid, also in acetic acid, but is soluble in these reagents if warm. For differentiating tests from calcite, see p. 146.

DUMORTIERITE. [Fig. 39. Pl. VIII.]

Chem. Comp. $\text{Al}_{20}\text{Si}_7\text{O}_{44}$; sometimes with B_2O_3 .

System. Orthorhombic.

Habit. Prismatic. Sometimes twinned about (110); also interpenetrated.

Structure. Crystalline; or in fibrous or columnar aggregates.

Cleavage. Good parallel to (100), less distinct parallel to (110). Parting observed parallel to (001).

Fracture. Uneven, but tends to coincide with parting planes.

Hardness. 7.

Spec. Grav. 3.26 to 3.36.

Lustre. Vitreous.

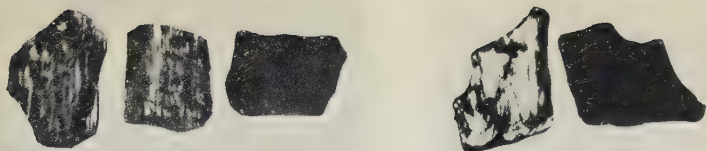
Colour. Colourless, greenish-blue, blue, grey, yellow-green, purple-grey, mauve. Transparent to translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Poor conductor.

Opt. Prop. R.I. high, $\alpha = 1.678$, $\beta = 1.686$, $\gamma = 1.689$. Birefringence high, $\gamma - \alpha = 0.011$. Optically biaxial, negative. $2V = 35^\circ$ to 40° . $2E = 37^\circ$ (Na). Optic axial plane parallel to (010). $Bxa = X \parallel c$ perpendicular to (001). $Y \parallel b$, $Z \parallel a$. Straight extinction. Strong dispersion, $\rho > \nu$ or $\rho < \nu$. Pleochroism marked: $X =$ deep blue, $Y =$ yellow-violet, $Z =$ colourless or green. Maximum absorption parallel to vertical axis, or in case of fibrous varieties, parallel to direction of elongation of fibres (orientation parallel to vibration plane of polariser).

Characters in Sediments. Presents unevenly terminated prismatic grains, sometimes with conspicuous striations parallel to prism edge. The resemblance to tourmaline is marked, especially in colour, but the refractive index of dumortierite is higher. Pleochroism is the chief diagnostic feature, the colour-change being very strong indeed; the mineral exhibits its pale colours in prismatic grains in a N.-S. position, and its dark colours in an E.-W. direction (orientation as above), as with staurolite. It is sometimes found as inclusions in cordierite, when it is surrounded with pleochroic haloes. Incipient alteration to muscovite is noted.



1. 2. 2a. 3a. 3b.

FIG. 39. DUMORTIERITE.

1. Blue prismatic grain with vertical striations, Bridport Sand, West Bay, Dorset. [x 130.]
2. Upper Greensand, Lulworth Cove, Dorset. [x 105.] (a) Position of minimum absorption, (b) Position of maximum absorption.
3. Bagshot Beds, 3 mls. W. of Ringwood, Hants. [x 130.] (a) and (b) as in 2 above. [1-3. Photos. by A. W. GROVES.]

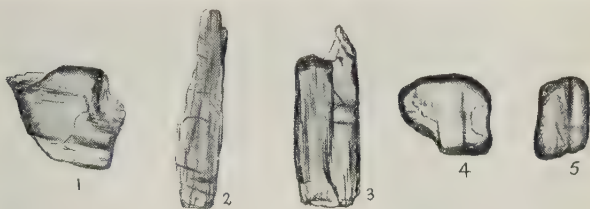


FIG. 41. ENSTATITE.

- 1-3. Shore Sand, Kynance, Cornwall. [x 40.]
4. do. Speeton, Yorkshire. [x 40.]
5. Blown Sand, Newgale, Pembrokeshire. [x 40.]



FIG. 42. EPIDOTE.

- 1-3. Shore Sand, Hornsea.
4. do. Denbighshire.
5. Tertiary Sandstone, New South Wales.
6. Alluvials, Nigeria. [All x 25.]



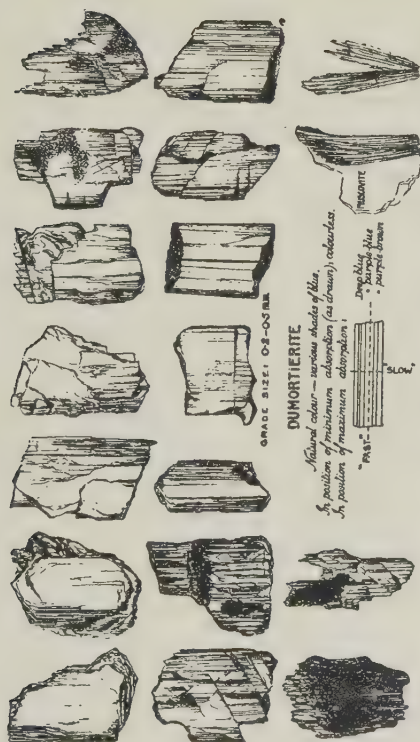


FIG. 40. Dumortierite from Dartmoor Granite (A. Brammall).

Occurrence. In the Bridport Sands (Inferior Oolite), West Bay, Dorset;¹ in sandstone of the Weald Clay, Surrey;² in the Upper Greensand, Lulworth Cove, Dorset;³ in the Blackheath Beds, Shirley, Surrey;⁴ in the Bagshot Beds of Bournemouth, Hants;⁵ in the Bagshot Beds, Wimborne, Dorset;⁶ Late Tertiary-Quaternary Sands, San Joaquin Valley, California, U.S.A.⁷ Later records: in the Gault Clay of Lulworth Cove, Dorset, and the Eocene of Great Haldon, Devonshire.⁸

Possible Sources of Derivation. Granite pegmatite; gneiss; metamorphic rocks.

REMARKS.—A. W. Groves has pointed out that most of the dumortierite he has found in English sediments is of a "Stephens Ink" blue colour. In all cases the greatest care is necessary in diagnosis, implying accurate optical measurements, to prevent any possible confusion with blue tourmaline, etc.

N.B.—Keen search for detrital dumortierite in British sediments is being made, following the records published by A. W. Groves. The discovery (while going to press) by J. N. Montgomery, of a grain in the Neolithic silts of Piltdown, Sussex, is of particular interest. This example is colourless, with strong violet absorption, thus differing from H. A. Hayward's Wealden examples and from those found by A. W. Groves. The only known occurrence of similar dumortierite to that of the Piltdown grain is in the Land's End Granite, according to Groves' observations. Other records since the above are from the Lower Greensand, Aylesbury, Bucks., and from the Oligocene of Totland Bay, I.O.W., by G. C. Flower and M. H. Lawson respectively.

¹ A. W. Groves, *Mineralogical Mag.*, xxi., 1928, pp. 489-492.

² H. A. Hayward, Recorded in "Supplement to Sedimentary Petrography," 1926, p. 64; A. W. Groves, *op. cit.*, p. 489.

³⁻⁶ A. W. Groves, *op. cit.*

⁷ R. D. Reed & J. P. Bailey, *Bull. Amer. Assoc. Pet. Geol.*, xi., 1927, p. 363.

⁸ A. W. Groves, personal communication.

General References.

W. Mackie, "Dumortierite in British Rocks," *Trans. Edinburgh Geol. Soc.*, xi., 1925, p. 352.

A. Brammall, "Dartmoor Detritals," *Proc. Geol. Assoc.*, xxxix., 1928, pp. 43-44.

P. G. H. Boswell, *Proc. Liverpool Geol. Soc.*, xiii., 1923, p. 268.

ENSTATITE. [Fig. 41. Pl. VIII.]

Chem. Comp. MgSiO_3 .

System. Orthorhombic.

Habit. Prismatic, bipyramidal.

Structure. Crystalline.

Cleavage. Good parallel to (110) and (010); less perfect parallel to (100).

Fracture. Uneven.

Hardness. 5 to 6.

Spec. Grav. 3.1 to 3.3.

Lustre. Vitreous to pearly; dull submetallic (bronze-like) in *Bronzite*.

Colour. Grey, yellow, greenish-white or olive green. Transparent to translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Poor conductor.

Opt. Prop. R.I. high, $\alpha = 1.665$, $\beta = 1.669$, $\gamma = 1.674$.

Birefringence low, $\gamma - \alpha = 0.009$. Optically biaxial, positive. Optic axial plane parallel to (010). Length slow. $Bxa = Z$ normal to (001). Straight extinction. $2V = 70^\circ$. $X \parallel a$ fast, $Y \parallel b$, $Z \parallel c$ slow. Optic axial dispersion slight: $\rho > \nu$. Pleochroism faint in the normal mineral (thick grains), stronger with increase of iron; $X = \text{yellow}$, $Y = \text{brownish-yellow}$, $Z = \text{green}$; distinctive for hypersthene (q.v.). *Bronzite* is an iron-bearing enstatite with optical properties intermedite between those of enstatite and hypersthene.

Characters in Sediments. Enstatite occurs in irregular or prismatic grains characterised by a somewhat "dirty" colour, vitreous or pearly lustre of cleavage flakes (most grains tend to be (110) flakes), straight extinction, high refractive index and low birefringence (lower than hypersthene); also by its lack of pleochroism (in thin grains), which together with its positive sign, serves to distinguish it from that mineral. Inclusions of magnetite, apatite or zircon are common, while alteration to a fibrous serpentinous aggregate (*Bastite*) is not uncommon. The submetallic lustre acquired by cleavage flakes of enstatite, together with the bronze colour, are due to internal decomposition, whereby oxide of iron tends to occupy cleavage cracks producing the char-

acteristic " Schiller-spath " or Schiller-structure, by which properties *Bronzite* is diagnosed; further alteration to serpentine is not infrequently observed in detrital bronzite.

Occurrence. Middle and Upper Old Red Sandstone of Scotland;¹ shore sand of Kynance Cove and other places, Lizard, Cornwall;² various foreign alluvial deposits, soils, etc.³

Possible Sources of Derivation. Basic and ultrabasic igneous rocks; less commonly metamorphosed sedimentary rocks.

REMARKS. — It should be noted that pure enstatite is non-magnetic, and can therefore be separated from hypersthene by electro-magnetic treatment. The mineral is not attacked by hydrochloric acid, but hypersthene is less stable in this respect.

¹ W. Mackie, *Trans. Edinburgh Geol. Soc.*, xi., 1923.

² Author's observations.

³ E. Tacconi, *Rendic. R. Ist. lomb.*, xxxiv., 1901, pp. 873-881

EPIDOTE. [Fig. 42. Pl. VIII.]

Chem. Comp. $\text{Ca}_2(\text{Al,OH})(\text{Al,Fe})_2(\text{SiO}_4)_3$. Fe may replace both Al and Ca.

System. Monoclinic.

Habit. Prismatic with dissimilar terminations. Often striated parallel to prism. Frequently twinned about (100), rarely parallel to (001).

Structure. Crystalline, fibrous, massive.

Cleavage. Perfect basal, parallel to (001). Imperfect parallel to (100).

Fracture. Uneven.

Hardness. 6 to 7.

Spec. Grav. 3.25 to 3.5.

Lustre. Vitreous, sometimes resinous.

Colour. Greenish-yellow, dark green, shades of brown.

Mag. Prop. Weakly magnetic.

Elect. Prop. Bad conductor.

Opt. Prop. R.I. very high, $\alpha = 1.729$, $\beta = 1.754$, $\gamma = 1.768$. Birefringence high, $\gamma - \alpha = 0.039$. Optically biaxial, negative. Optic axial plane parallel to (010), normal to principal cleavage. $Bxa = X$ inclined at $-2^\circ 30'$ to c. $Y \parallel b$. $2V \approx 92^\circ$ (varies with amount of Fe_2O_3 present). Pleochroism weak: Y greenish-yellow to X and Z colourless, noticeable in thick grains. Strong dispersion, $\rho > \nu$.

Characters in Sediments. Irregular and rather angular grains common, the flattened "platy" forms often exhibiting partial (compass-needle) interference figure, due to emergence of one optic axis. Pale yellowish-green subangular grains, like small chips of broken "bottle-glass," are very characteristic of many sands, and are remarkable for their transparency. A further diagnostic feature is the brilliant green-purple-red (ringed) interference tints observed in most clear individuals.

Occurrence. In the Old Red Sandstone of the West Midlands;¹ in the Permian Rocks of the Torquay Promontory;² in the Upper Lias—Lower Inferior Oolite of

¹ W. F. Fleet, *Geol. Mag.*, lxiii., 1926, p. 513.

² W. G. Shannon, *Proc. Geol. Assoc.*, xxxviii., 1927, p.

the West of England;¹ in the Northampton Ironstone;² in the Sandgate Beds of Surrey;³ in the Upper Greensand of Surrey;⁴ in Eocene and Oligocene sands of the Haldon Hills and Bovey Tracey respectively, Devon;⁵ in the Bagshot Beds of Essex;⁶ in Miocene-Pliocene sands of California⁷ (some of the Pliocene oil-sands of the Los Angeles Basin are particularly rich in epidote⁸); in the Pliocene deposits of West Cornwall;⁹ in the later Tertiary deposits of East England;¹⁰ in surface deposits of S.E. Devon;¹¹ in dune sands of South Wales;¹² in blown sands, Newgale, Pembrokeshire.¹³

Possible Sources of Derivation. Crystalline metamorphic rocks, especially altered impure limestones. Also from highly altered igneous rocks originally rich in ferromagnesian minerals.

REMARKS.—In certain local environments, involving crystalline schists, amphibolites, etc., as contributors to sedimentary deposits, detrital Zoisite (the orthorhombic member of the epidote group) may be met with; detrital Clinozoisite is also known: see page 259.

¹ P. G. H. Boswell, *Geol. Mag.*, lxi., 1924, pp. 262-3.

² J. G. A. Skerl, *Proc. Geol. Assoc.*, xxxviii., 1927, p. 383.

^{3, 4} G. M. Davies, *Proc. Croydon Nat. Hist. Soc.*, 1915-16, pp. 84-5.

⁵ P. G. H. Boswell, *Q.J.G.S.*, lxxix., 1923, p. 226.

⁶ S. W. Wooldridge, *Proc. Geol. Assoc.*, xxxv., 1924, p. 376.

⁷ R. D. Reed & J. P. Bailey, *Bull. Amer. Assoc. Pet. Geol.*, xi., 1927, pp. 359-363, *et seq.*

⁸ Author's observations.

⁹ H. B. Milner, *Q.J.G.S.*, lxxviii., 1922, p. 361.

¹⁰ I. S. Double, *Proc. Geol. Assoc.*, xxxv., 1924, pp. 340-341.

¹¹ W. G. Shannon, *Geol. Mag.*, lxiv., 1927, pp. 147, 149.

¹² A. Stuart, *Proc. Geol. Assoc.*, xxxv., 1924, p. 324.

¹³ Author's observations.

General Reference.

- M. I. Goldman, *Amer. Journ. Sci.*, xxxix., 1915, pp. 277-280 (for significance of scarce epidote in sediments, as exemplified by the Catahoula Sandstone of Texas).

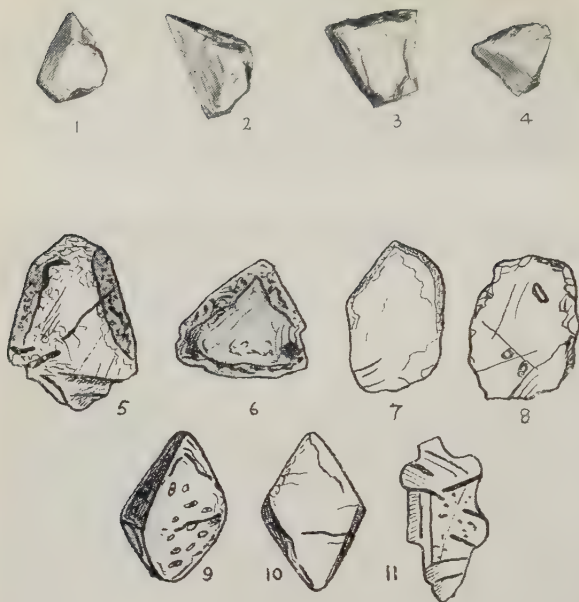


FIG. 43. FLUORITE.

1-4, Red River Sand, Cornwall [x 40]; 5-7, Shore Sand, Cornwall; 8, Blow Sand, Lelant, Cornwall (with glass inclusions); 9, Blown Sand, Hayle, Cornwall (with fluid inclusions); 10, Octahedron (loc. as 8); 11, Irregular grain showing octahedral cleavage traces (loc. as 10). [5-11, x 25.]

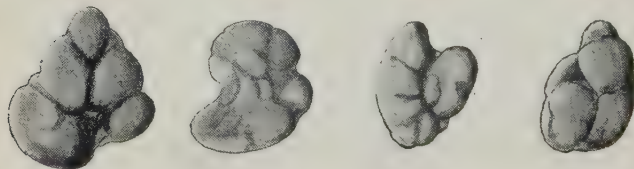


FIG. 45. Glauconite (Casts of *Foraminifera*), Upper Greensand, Chaldon Herring, Dorset. [x 50.]

To face page 177.

PLATE IX

FLUORITE. [Fig. 43. Pl. IX.]

Chem. Comp. CaF_2 .

System. Cubic.

Habit. Either simple or modified cube; interpenetrant twins common about (111).

Structure. Crystalline, compact, massive.

Cleavage. Perfect parallel to (111).

Fracture. Conchoidal.

Hardness. 4.

Spec. Grav. 3.18 to 3.189.

Lustre. Vitreous.

Colour. Commonly colourless; white, green, blue or purple; also pink, brown and intermediate shades. Transparent to translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Bad conductor.

Opt. Prop. R.I. very low. $n=1.4336$. Optically isotropic. May show anomalous polarisation due to internal strain.

Characters in Sediments. Frequently occurs as octahedral cleavage fragments, subangular or irregular. Rounded grains rare. Triangular plates with modified edges sometimes found. Detrital grains of this mineral are often violet in colour, though the colouring matter may not permeate the whole grain, thus rendering it "blotchy." Inclusions of iron-ores, manganese, hydrocarbon (?) or fluid. Diagnosed by its octahedral tendency, prominent relief and lower R.I. than Canada balsam, also by its isotropism.

Occurrence. In the Old Red Sandstone, Cardiff;¹ in the Bunter Pebble Bed, West of England;² in the New Red Sandstone, West of England;³ in Dartmoor detritals;⁴ in shore sand, St. Ives Bay, Cornwall;⁵ in Red River sand, Camborne, Cornwall.⁶

Possible Sources of Derivation. Acid igneous rocks, metamorphic rocks and metalliferous veins. Also limestones.

¹ A. Heard & R. Davies, *Q.J.G.S.*, lxxx., 1924, pp. 489-519.

² H. H. Thomas, *Q.J.G.S.*, lviii., 1902, p. 620.

³ H. H. Thomas, *Q.J.G.S.*, lxx., 1909, p. 231.

⁴ A. Brammall, *Proc. Geol. Assoc.*, xxxix., 1928, pp. 37-38.

⁵ T. Crook & G. M. Davies, *Geol. Mag.*, 1909, p. 122.

⁶ Author's observations.

GALENA.

[Fig. 44.]

Chem. Comp. PbS.*System.* Cubic.*Habit.* Cube, octahedron or combination of both.*Structure.* Crystalline or massive.*Cleavage.* Perfect parallel to (100).*Fracture.* Even.*Hardness.* 2.5 to 2.75.*Spec. Grav.* 7.4 to 7.6.*Lustre.* Metallic.*Colour.* Lead-grey. Opaque.*Mag. Prop.* Non-magnetic.*Elect. Prop.* Non-conductor.

Characters in Sediments. Detrital galena is characterized by its colour, lustre, cubic form (usually cleavage), or by its occurrence as small, shapeless particles of typical lead-grey metallic lustre. With large grains, a black or blue superficial tarnish may be noted. It is not a common constituent of sediments unless authigenic, or locally where sulphide veins have contributed to sedimentary deposits.

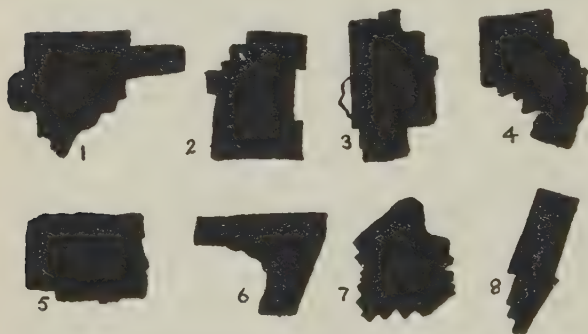


FIG. 44. Galena from Triassic Sandstone, Alderley Edge, Cheshire. [x 50.]

Occurrence. Old Red Sandstone beneath London (Richmond boring, 1882);¹ in the Triassic Sandstones of

¹ J. W. Judd, *Q.J.G.S.*, xl, 1884, p. 749.

Alderley Edge, Cheshire,¹ in the Fullers Earth (Aptian) of Redhill, Surrey.²

Possible Sources of Derivation. Veins and beds in limestones; metallic sulphides with quartz or other gangue material; silver-lead ores; rarely in gneiss, granite pegmatite, etc.

¹ Author's observation. (N.B.—Much of this material is clearly an impregnation product, *i.e.*, authigenic). See also Holmes, "Petrographic Methods," p. 191.

² G. M. Davies, *Proc. and Trans. Croydon Nat. Hist. Soc.*, 1915 16, p. 86.

GARNET. [Fig. 45. Pl. X.]

Chem. Comp. Group of orthosilicates with general formula $R''_3R'''_2(SiO_4)_3$. R'' may be Ca, Mg, Fe'' or Mn. R''' may be Al, Fe''' or Cr. Species: *Grossularite* (Ca), *Pyrope* (Mg), *Almandine* (Fe), *Spessartite* (Mn), *Andradite* (CaFe), *Uvarovite* (Cr).

System. Cubic.

Habit. Dodecahedral (110), trapezohedral (211), or combination of both forms. Twinning unknown.

Structure. Crystalline, massive.

Cleavage. Imperfect dodecahedral, parallel to (110).

Fracture. Irregular, subconchoidal.

Hardness. 7.

Spec. Grav. 3.8, but varies considerably with composition.

Lustre. Vitreous, resinous.

Colour. Varies with species. *Grossularite*, white, greenish-yellow, brown or pale red. *Pyrope*, deep red to black. *Almandine*, deep brownish-red to ruby red. *Spessartite*, brown. *Andradite*, yellow, brown, green, black. *Uvarovite*, emerald green.

Mag. Prop. Moderately magnetic.

Elect. Prop. Poor conductor.

Opt. Prop. R.I. high, $n = 1.71-1.89$. Optically isotropic, though some crystals exhibit anomalous interference colours due to strain. *Almandine* is invariably isotropic, likewise *Pyrope* and *Spessartite*: *Andradite*, *Uvarovite* and *Grossularite* frequently exhibit anomalous optical properties, *i.e.*, interference, biaxial figure with fairly wide optic axial angle, and usually a negative sign. All such varieties tend to show strong dispersion.

Characters in Sediments. Detrital garnets are commonly irregular, often fractured, sometimes well rounded. Pale pink grains (*Almandine*) are the most prevalent. Grains frequently void of recognizable crystal faces. Platy forms, determined by (110) cleavage, showing subconchoidal fracture or marked re-entrant angles are sometimes met with. Inclusions common in many instances. Among the latter Brammall has noted quartz, feldspar, apatite, zircon, biotite, rutile and iron-ore in the Dartmoor detritals. The surface char-



FIG. 46. GARNET from Different British Stratigraphical Horizons.

1, Torridonian (after Bosworth); 2, Quartzite (Cambrian), Malvern; 3, Hollybush Sandstone (Cambrian), Malvern; 4, May Hill Sandstone (Silurian), Malvern; 5, 6, 7, Millstone Grit, Northumberland; 8, Fireclay, Coal Measures, Ferguslie, Paisley, N.B.; 9, Permian, Tynemouth, Northumberland; 10, 11, Bunter, Hoyle, Cheshire; 12, Lias, Napton, Rugby; 13, Northampton Sands, Northampton; 14, Corallian, Abbotsbury, Dorset; 15, Portland Sand, Portland, Dorset; 16, Ashdown Sand (Wealden), Hastings, Sussex; 17, Upper Greensand, Telsworth, Oxon.; 18, Thanet Sand, Plumstead, Kent; 19, Woolwich and Reading Sand, St. Albans; 20, Blackheath Beds, Elmstead, Surrey; 21, Bagshot Sands, Bournemouth; 22, Pliocene, Bentley, Suffolk; 23, Glacial Sand, Kimpton, Herts.; 24, Shore Sand, Speeton, Yorks. [All $\times 25$.]

acters of many detrital garnets are often very striking and repay careful study; pitting, grooving, spotting, rectangular patterning, deep colour-staining and sometimes "etched" appearance, tend to individualize types. Shape and size are also significant.

Occurrence. Garnet is one of the most widespread and persistent constituents of detrital sediments, and in the British Isles is found in the oldest to the youngest rocks with very few exceptions. Among the best horizons for this species are:—Old Red Sandstone, Herefordshire; Calcareous Sandstone, Midlothian region, Scotland; Millstone Grit, Northumberland, Durham and Yorkshire; Permian rocks, South Devon; Upper Keuper, Leicestershire; Estuarine Sandstones, Yorkshire and Northamptonshire; various Glacial Sands and Gravels of East Anglia, Plateau Gravels of the London Basin and shore sands of West Cornwall (Marazion, St. Ives). (N.B.—The comparative scarcity of garnet in the Tertiary deposits of Cornwall is noteworthy: see reference * below).

Possible Sources of Derivation. Igneous and metamorphic rocks, particularly crystalline gneisses and schists. Alluvial deposits.

REMARKS.—Garnet varies widely in detrital sediments, specific physical features often typifying grains from definite horizons; on this account it is of great importance for correlation purposes, and also for suggesting the conditions under which deposition took place.

General References.

T. O. Bosworth, "Keuper Marls around Charnwood," Leicestershire, *Leicester Lit. & Phil. Soc.*, pp. 96-100 & figs. 44, 45.

*P. G. H. Boswell, *Q.J.G.S.*, lxxix., 1923, pp. 221-223.

A. Brammall, *Proc. Geol. Assoc.*, xxxix., 1928, p. 35.

C. Raeburn & H. B. Milner, "Alluvial Prospecting," 1927, pp. 389-393 and plate xvi. (for alluvial occurrences).

A. Stuart, *Proc. Geol. Assoc.*, xxxv., 1924, pp. 321 & fig. 27.

GLAUCONITE. [Fig. 45. Pl. IX.]

Chem. Comp. Silicate of K, Fe, Al with H_2O .

System. Non-crystalline.

Structure. Amorphous. Earthy aggregates, granular, fibrous or as irregular grains. Some varieties show good lamellar development. Organic structures common.

Hardness. 2.

Spec. Grav. 2.2 to 2.84.

Lustre. Dull, sometimes vitreous.

Colour. Various shades of green, blackish-yellow. Brown when altered.

Mag. Prop. Moderately magnetic.

Elect. Prop. Poor conductor.

Opt. Prop. R.I. $n=1.61$. Birefringence variable, but aggregates commonly present low polarisation tints. Optically biaxial in lamellar aggregates. Some varieties decidedly pleochroic: green to yellowish-green; seen to advantage in lamellar types.

Characters in Sediments. Rounded or irregular grains or aggregates, usually characteristic of the "light" material of certain sediments. Frequently occurs as casts of *foraminifera*. Commonly dark green in colour, if not altogether opaque; strong tendency to show decomposition to limonite. Liable to confusion with certain types of chlorite (q.v.).

Occurrence. In the Cambrian, Ordovician, Silurian, Old Red Sandstone of the Midlands;¹ in the Upper Lias-Lower Inferior Oolite of the West of England;² Lower Greensand (especially the Sandgate Beds) of the Weald;³ in the Gault, Upper Greensand and Lower Chalk of Surrey;⁴ in the Upper Greensand of the Weymouth district, Dorset;⁵ in the Greensand of the

¹ W. F. Fleet, *Geol. Mag.*, lxii., 1925, pp. 101, 102, 104, 106, 126.

² P. G. H. Boswell, *Geol. Mag.*, lxi., 1924, pp. 257, 258, 262

^{3, 4} G. M. Davies, *Proc. Croydon Nat. Hist. Soc.*, 1915-16, pp. 82-85, 92.

⁵ Author's observations.

Haldon Hills, Devon;¹ in the Thanet Beds, Reading Beds and London Clay of the N.E. part of the London Basin;² detrital glauconite in the Oligocene beds of Bovey Tracey, Devon;³ in the Bagshot Beds of Essex;⁴ in the Pliocene deposits of West Cornwall;⁵ in the later Tertiary deposits of the East of England;⁶ in various valley gravels and loams of Surrey and the London district.⁷

Possible Sources of Derivation. Sedimentary rocks, more rarely from amygdaloidal lavas. Frequently of organic origin.

REMARKS. — Glauconite is a mineral of considerable geological interest. It occurs in abundance at certain stratigraphical horizons, especially in the Cretaceous Greensands. Its properties undoubtedly vary largely with the amount of iron present, this factor affecting the S.G., which in some cases is >2.80 . Most varieties are decomposed by HCl, hence in preliminary treatment of samples with this acid much of the glauconite may be lost. Its prolific occurrence in the Greensands would seem to be a function of its chemical stability in this instance, rather than of accentuated development at that epoch. There is no reason to suppose that it was initially less common in older than in younger sediments; on the contrary, its characters frequently suggest derivation and redeposition from pre-existing deposits.* (See particularly pp. 443-44 of this volume, references there cited, also recent work by A. F. Hallimond (below)).

¹ P. G. H. Boswell, *Q.J.G.S.*, lxxix., 1923, pp. 209, 226.

² P. G. H. Boswell, *Q.J.G.S.*, lxxi., 1915, table iv & pp. 557, 580.

³ P. G. H. Boswell, *Q.J.G.S.*, lxxix., 1923, pp. 218, 220.

⁴ S. W. Wooldridge, *Proc. Geol. Assoc.*, xxxv., 1924, pp. 364, 376.

⁵ H. B. Milner, *Q.J.G.S.*, lxxviii., 1922, pp. 348-377.

⁶ I. S. Double, *Proc. Geol. Assoc.*, xxxv., 1924, pp. 342-3.

⁷ G. M. Davies, *op. cit.*, pp. 78-82.

General References.

* P. G. H. Boswell, "The Application of Petrographical and Quantitative Methods to Stratigraphy," *Geol. Mag.*, 1916, p. 107, etc.

F. W. Clark, "The Data of Geochemistry," *U.S.G.S.*, Bull. 770, 1924, pp. 137-8, 510-522, 584.

A. F. Hallimond, *Mineralogical Mag.*, xix., 1922, p. 330.

GLAUCOPHANE. [Fig. 47. Pl. XI.]

Chem. Comp. $\text{NaAl}(\text{SiO}_3)_2 \cdot (\text{Fe.Mg})\text{SiO}_3$.

System. Monoclinic.

Habit. Prismatic, short "stumpy" crystals.

Structure. Crystalline.

Cleavage. Good parallel to (110).

Fracture. Uneven.

Hardness. 5 to 6.

Spec. Grav. 2.991.

Lustre. Vitreous, pearly on cleavage fragments.

Colour. Colourless, pale blue, grey-blue to bluish-black.

Mag. Prop. Moderately magnetic.

Elect. Prop. Moderate conductor.

Opt. Prop. R.I. high, $\alpha = 1.6212$, $\beta = 1.6381$, $\gamma = 1.6390$. Birefringence high, $\gamma - \alpha = 0.0178$. Optically biaxial negative. Optic axial plane parallel to (010). Bxa X makes an angle of 4° to 6° with the vertical crystallographical axis in the obtuse angle β . Length and cleavage direction slow. $Y \parallel b$, $Z \wedge c = \pm 5^\circ$. Oblique extinction, 3° to 11° , rarely 16° to 22° in partially altered forms. Sometimes fails to extinguish in any position. Pleochroism very marked, Z blue, Y lavender or violet, X colourless to yellow or yellow-green. Dispersion strong, $p < v$.

Characters in Sediments. Commonly occurs as entirely irregular grains void of recognizable crystal faces, though elongation in the direction of the principal crystallographic axis tends to produce suggestive prismatic grains, which may or may not exhibit the characteristic pleochroism by which this species is invariably diagnosed. Many grains are undoubtedly derived by (110) cleavage. Another type is ragged in appearance, not unlike some varieties of tremolite or (save the colour) actinolite. Striae parallel to the principal axis occasionally observed. Inclusions are usually common, e.g., magnetite, rutile, ? titanite, apatite.

Occurrence. In the Upper Lias—Lower Inferior Oolite of the West of England;¹ in the Northampton Ironstone;²

¹ P. G. H. Boswell, *Geol. Mag.*, lxi., 1924, p. 256.

² J. G. A. Skerl, *Proc. Geol. Assoc.*, xxxviii., 1927, p. 383.



FIG. 47. GLAUCOPHANE AND HORNBLLENDE.

- 1, 3. Glaucophane from Miocene Sands, Trinidad. [x 70.]
 2, 4. Hornblende from Miocene Sands, Trinidad. [x 70.]
 5. Glaucophane from Blown Sands, Newgale, Pembrokeshire. [x 70.]
 6. Glaucophane from Glacial Sands, Withybush, Haverfordwest, Pembrokeshire. [x 40.]
 7. Hornblende from Blown Sands, Newgale, Pembrokeshire. [x 70.]



FIG. 48. GYPSUM.

- A. 1-3. Recent Sand, Bulawayo, Rhodesia. [x 30.] B. 1-4. London Clay, Thornton Heath, Surrey. [x 40.] N.B. -B. 1, 3 and 4 are twinned on (100). From Brush-drawings by F. Smithson.

in Lias—Inferior Oolite of the Midlands;¹ in the Kimmeridgian-Portlandian sands of the South of England;² in the Ashdown Sand (Wealden) of Hastings, Sussex;³ in the Oldhaven and Reading Beds of the London Basin;⁴ in Glacial Deposits of East Anglia;⁵ in wind-blown deposits of Guernsey;⁶ in blown sands from Newgale, Pembrokeshire;⁷ in sands of pre-glacial screes in Anglesey;⁸ also shore sands of that island;⁹ in valley deposits in Surrey.¹⁰

Possible Sources of Derivation. Metamorphic rocks, especially schistose types. Eclogites. Crystalline limestones.

REMARKS.—The more thorough searching of sediments in recent years has brought to light the widespread occurrence of this interesting mineral, and, although seldom common in any one deposit, it has been shown by different investigators to occur consistently at certain horizons over large areas. In the author's experience it is especially prevalent in Miocene rocks (a coincidence) in countries as far removed as Trinidad, Venezuela, California, Italy, Iraq and Persia. In this respect it achieves the same distinction that andalusite has in connexion with its occurrence in Pliocene deposits (p. 127). Prof. Boswell remarks on the frequent association of glaucophane and chloritoid.¹

¹ P. G. H. Boswell, *Trans. Geol. Soc. Glasgow*, xviii., 1926-27, p. 139.

² E. Neaverson, *Proc. Geol. Assoc.*, xxxvi., 1925, p. 250.

³ H. B. Milner, *Proc. Geol. Assoc.*, xxxvi., 1925, p. 315.

^{4-6, 8, 10} P. G. H. Boswell, *op. cit.* (1926-27).

^{7, 9} Author's observations.

GRAPHITE.

Chem. Comp. Carbon, sometimes with iron and silica.

System. Rhombohedral.

Habit. Tabular (six-sided) plates or flakes; sometimes striated parallel to trace of unit rhombohedron (10 $\bar{1}$ 1).

Structure. Crystalline, columnar, radiate, granular, compact, earthy.

Cleavage. Perfect parallel to (0001); indistinct parallel to (10 $\bar{1}$ 1).

Fracture. Irregular.

Hardness. 1 to 2.

Spec. Grav. 2.09 to 2.23.

Lustre. Metallic, sometimes dull, "soot-black."

Colour. Steel-grey to "soot-black." Opaque.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Characters in Sediments. Occurs in the form of rounded or irregular dull black grains, recognized chiefly by their appearance in reflected light.

Occurrence. In Devonian limestones of the Torquay district ("Carbon");¹ shore sands of the coast of North Cornwall.²

Possible Sources of Derivation. Metamorphic rocks: gneisses, phyllites, schists, altered limestones, quartzites.

REMARKS.—Detrital graphite is essentially a local species, hardly to be expected in ordinary sediments unless graphite-rich rocks have been laid under contribution to them. Certain shore sands lying close to phyllites which have undergone disintegration yield both free and composite grains of graphite, in the latter case associated generally with quartz.

¹ W. G. Shannon, *Proc. Geol. Assoc.*, xxxix., 1928, p. 150.

² Author's observations. See also P. G. H. Boswell, *Proc. Liverpool Geol. Soc.*, xiii., 1923, p. 268.

GYPSUM (Selenite). [Fig. 48. Pl. XI.]

Chem. Comp. $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$.

System. Monoclinic.

Habit. Prismatic, flattened parallel to (010). Frequently twinned on (100), less commonly on (101).

Structure. Crystalline, fibrous, massive or granular.

Cleavage. Good parallel to (010), also parallel to (100).

Fracture. None. Glide planes may be developed parallel to (103) and (309).

Hardness. 1.5 to 2.

Spec. Grav. 2.314 to 2.328.

Lustre. Vitreous to dull; pearly on (010) faces.

Colour. Colourless, white, sometimes stained by impurity. Transparent to translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Bad conductor.

Opt. Prop. R.I. low, $\alpha = 1.5208$, $\beta = 1.5229$, $\gamma = 1.5305$.

Birefringence low, $\gamma - \alpha = 0.0097$. Optically biaxial, positive. Optic axial plane parallel to (010). $Bxa = Z$ inclined at $37\frac{1}{2}^\circ$ to normal of (100) and makes the complementary angle of $52^\circ 30'$ with the c axis in the obtuse angle β . $Y \parallel b$. Fibres fast $\parallel$ length. Optic axial angle large, $2E = 95^\circ$, $2V = 58^\circ$. (010) folia give extinction angles of 13° and 37° . Strong inclined dispersion, $\rho > \nu$. Optical properties vary considerably with temperature.

Characters in Sediments. Found as colourless, well formed crystals (Selenite), often somewhat rounded; or as "platy" cleavage fragments of a pseudo-rhombohedral character and determined by (010) cleavage. Other developments noted include fibrous and matted types, spherulites and radiating clusters; these frequently show brush-polarisation; twinned crystals, about (100), also occur, the plane of composition being represented by a sharply defined line from which the two halves of the crystal extinguish at an angle of $37^\circ 30'$. Twinned and corroded selenites have been described

from the London Clay and are good examples of these developments.⁶ The irregularly shaped grains and aggregates of gypsum (as distinct from the crystalline selenite) met with in sandstones, etc., are probably derived from the disintegration of the mineral occurring in the form of a cementing medium; in this respect the grains resemble the haphazard forms of barite (*q.v.*) from which, however, they are readily distinguished by optical properties. Immature developments from anhydrite (*q.v.*) are common in some rocks; such grains have a higher S.G. than normal gypsum, also a higher R.I. than Canada balsam, though the characteristic properties of anhydrite, *e.g.*, cleavage, form, are usually obscured. In the crystalline forms (selenite), zoning is often a feature, the zones being picked out by iron-ore inclusions; of the latter, rutile, apatite, hæmatite, magnetite are among those most commonly noted. Diagonal striæ common. Selenite and gypsum are both diagnosed primarily by their low S.G., habit, colour and low R.I. (lower than Canada balsam), the crystalline variety, by very distinctive optical properties, as noted above.

Occurrence. In the New Red Sandstone of the West of England;¹ massive gypsum in the Triassic deposits of the Midlands, notably Nottinghamshire² and Leicestershire³; selenite in the Kimmeridge Clay, Shotover Hill, Oxford;⁴ also in the Upper Kimmeridgian of Buckinghamshire;⁵ in the London Clay of Thornton Heath, Surrey,⁶ and at Harefield, Middlesex.⁷ Many of the Miocene clays and marls of different countries yield beautiful varieties of selenite, *e.g.*, the Naparima Marls of Trinidad, the Lower Fars of Iraq and Persia,⁸ the latter countries famous, also, for their vast developments of massive gypsum.

¹ H. H. Thomas, *Q.J.G.S.*, lxx., 1909, p. 231.

² W. H. Richardson, *Mineralogical Mag.*, xix., 1921, pp. 196-207.

³ T. O. Bosworth, "Keuper Marls around Charnwood," Leicestershire, *Leicester Lit. & Phil. Soc.*, ch. ix.

⁴ Well-known locality.

⁵ E. Neaverson, *Proc. Geol. Assoc.*, xxxvi., 1925, p. 253.

⁶ G. M. Davies, *Proc. Croydon Nat. Hist. Soc.*, 1915-16, p. 95.

^{7, 8} Author's observations.

Possible Sources of Derivation. Sedimentary rocks, saline deposits, from volcanic regions, and metalliferous veins.

REMARKS.—There is good reason to believe that crystalline gypsum (selenite) occurs far more commonly in argillaceous rocks in the British Isles than the scanty records available would suggest. In washing out the light materials of such sediments, much of this gypsum may be lost or otherwise overlooked. It is certainly an interesting species and, like anhydrite, repays study, especially for the many and varied forms exhibited. Its stratigraphical significance is referred to on p. 444.

HÆMATITE.

Chem. Comp. Fe_2O_3 .

System. Rhombohedral.

Habit. Euhedral; tabular parallel to (0001); platy.

Structure. Crystalline, laminated, massive or earthy.

Cleavage. Doubtful. Parting parallel to (0001) and (10 $\bar{1}$ 1), due to lamellar twinning.

Fracture. Subconchoidal, irregular.

Hardness. 5.5 to 6.5.

Spec. Grav. 4.9 to 5.3.

Lustre. Brilliant, metallic. Earthy varieties red.

Colour. Steel-grey. Translucent to opaque.

Mag. Prop. Moderately magnetic.

Elect. Prop. Good conductor.

Opt. Prop. Opaque in thick scales or grains. Translucent plates show high R.I., $\omega = 3.22$, $\epsilon = 2.94$, and high birefringence, $\omega - \epsilon = 0.28$, polarisation tint often masked by natural colour. Optically uniaxial, negative. Said to be pleochroic in sections perpendicular to basal plane: brownish-red to yellowish-red.†

Characters in Sediments. Commonly found as rounded earthy grains of a reddish-brown colour by reflected light, which is very characteristic. More rarely as rhombohedral grains or "platy" forms with splendid lustre. Thomas has described "minute botryoidal grains, made up of spheroidal masses with radiate structure which give a black cross between crossed nicols."³

Occurrence. In Devonian sediments of the Torquay district;¹ in Permian rocks of the Torquay Promontory;² in the New Red Sandstone of the West of England;³ in the Keuper Marls of Charnwood, Leicestershire;⁴ in the Fairlight Clay (Wealden) of Sussex;⁵ in the Thanet

† Iddings: *Rock Minerals*, 1906, p. 503.

¹ W. G. Shannon, *Proc. Geol. Assoc.*, xxxix., 1928, p. 140, etc.

² W. G. Shannon, *Proc. Geol. Assoc.*, xxviii., 1927, p. 134.

³ H. H. Thomas, *Q.J.G.S.*, lxx., 1909, p. 232.

⁴ T. O. Bosworth, "Keuper Marls around Charnwood," Leicestershire, *Leicester Lit. & Phil. Soc.*, p. 94.

⁵ H. B. Milner, *Proc. Geol. Assoc.*, xxxvi., 1925, p. 315.

Beds, Reading Beds and London Clay of the N.E. part of the London Basin;¹ in the dune sands of South Wales;² in surface deposits of S.E. Devon;³ in Dartmoor detritals.⁴

Possible Sources of Derivation. Igneous and metamorphic rocks; metalliferous veins; limestones.

REMARKS.—Hæmatite occurs in sediments both as a primary and secondary constituent. In the latter case its partial alteration to limonite may frequently be observed. A common "cementing" medium in sandstones.

¹ P. G. H. Boswell, *Q.J.G.S.*, lxxi., 1915, table iv., pp. 576, 578.

² A. Stuart, *Proc. Geol. Assoc.*, xxxv., 1924, p. 320.

³ W. G. Shannon, *Geol. Mag.*, lxiv., 1927, pp. 146, 148.

⁴ A. Brammall, *Proc. Geol. Assoc.*, xxxix., 1928, pp. 35-6.

HORNBLENDE. (Fig. 47. Pl. XI.

Chem. Comp. Complex silicate of Fe, Mg, Ca, Al and Na.

System. Monoclinic.

Habit. Prismatic.

Structure. Slender prismatic or acicular crystals. Fibrous (Actinolite), or compact.

Cleavage. Parallel to (110) usually well developed. Less distinct parallel to (100) and (010). Cleavage traces in cross sections (normal to prism zone) intersect at angle of 124° . Parting observed in twin crystals parallel to (100) and (010).

Fracture. Uneven, subconchoidal. Frequently occurs at right angles to prismatic cleavage.

Hardness. 5 to 6.

Spec. Grav. 3 to 3.3, varying with composition.

Lustre. Vitreous.

Colour. Dark green, brown, black. Translucent.

Mag. Prop. Moderately magnetic.

Elect. Prop. Moderate conductor.

Opt. Prop. R.I. high, $a = 1.6298$, $\beta = 1.6431$, $\gamma = 1.6561$.

Birefringence low, $\gamma - a = 0.0263$. Optically biaxial, negative. Length and cleavage trace slow. $Y \parallel b$, $Z \wedge c = 15^{\circ} - 25^{\circ}$. Optic axial plane parallel to (010). Bxa inclined at low angle to normal of (100). Oblique extinction, varies from 12° to 18° . Pleochroism varies, maximum absorption being in direction parallel to Z, i.e., $Z > Y > X$: X = yellow or pale green, Y = straw-yellow or yellow-green, Z = brown or dark green. Dispersion, $\rho < \nu$.

Characters in Sediments. Green varieties of hornblende are most characteristic of detrital sediments, the brown types being rare (p. 444). Grains are usually in the form of elongated, "platy" cleavage flakes determined by (110), and with frayed ends. (010) grains or cleavage flakes often noted. Prismatic striæ are a feature of certain types. The colour may be unevenly distributed in the grain, being densest in the middle and becoming gradually paler towards the boundaries, especially the terminations, where the pleochroism is often best observed. Pleochroism is a variable factor; some grains are non-pleochroic; most show weak colour-change, a few exhibit strong properties in this respect, especially the blue-green (soda-bearing) and

deep brown (Barkevicite) types. The common pleochroism noted is the change from the pale colour (in the N.-S. position) to darker shades in the E.-W. position (the latter vibrations parallel to the short axis of the polariser). Barkevicite preserves much the same characters as common hornblende; it is usually in (010) flakes, shows perfect prismatic cleavage, and is strongly pleochroic (black-brown E.-W. to yellow-brown N.-S., orientation as above); the length is the direction of slow vibration. Extinction is from 12° to 15° . Inclusions of magnetite, rutile, apatite and titanite have been observed in common hornblende, but they are not particularly frequent. Alteration is mainly to chloritic matter, and all stages of decomposition are detectable in detrital grains. Very rarely unusually blue grains suggest Riebeckite; the blue-green varieties suggest Arfvedsonite; the colourless variety, Tremolite, is not infrequent (p. 250), while the fibrous Actinolite is a sporadic development (p. 121). All amphiboles are diagnosed chiefly by their form, colour, marked prismatic cleavage, weak pleochroism and characteristic extinction angles.

Occurrence. In Devonian sediments of the Torquay district;¹ in the Sandringham Sands, Snettisham Clay and Carstone (Lower Greensand) of Norfolk;² greenish-blue type in the Carstone of Hunstanton, Norfolk;³ in the Red Chalk of Hunstanton;⁴ in the Eocene and Oligocene deposits of the Haldon Hills and Bovey Tracey, Devon, respectively;⁵ in the Thanet Beds and London Clay of the N.E. part of the London Basin;⁶ in the Bagshot Beds of Essex⁷ and of N.W. London;⁸ in the Pliocene sands of Bentley, Suffolk and Walton-on-Naze, Essex;⁹ in the later Tertiary deposits of the East of

¹ W. G. Shannon, *Proc. Geol. Assoc.*, xxxix., 1928, pp. 137-146.

² H. C. Versey & C. Carter, *Proc. Yorks. Geol. Soc.*, xx., 1926, pp. 350-358.

³ R. H. Rastall, *Geol. Mag.*, 1919, p. 214.

⁴ H. C. Versey & C. Carter, *op. cit.*, p. 360.

⁵ P. G. H. Boswell, *Q.J.G.S.*, lxxix., 1923, p. 226.

⁶ P. G. H. Boswell, *Q.J.G.S.*, lxxi., 1915, pp. 577, 580.

⁷ S. W. Wooldridge, *Proc. Geol. Assoc.*, xxxv., 1924, p. 377.

^{8, 9} Author's observations,

England;¹ in the dune sands of South Wales (including barkevicite);² in glacial sands, etc., of the Dublin district;³ in shore sands of Guernsey;⁴ in blown sands from Newgale, Pembrokeshire.⁵

Possible Sources of Derivation. Igneous and metamorphic rocks, especially granite, syenite, diorite and equivalent volcanic types, and also hornblende schists, etc.

¹ I. S. Double, *Proc. Geol. Assoc.*, xxxv., 1924, p. 341.

² A. Stuart, *Proc. Geol. Assoc.*, xxxv., 1924, p. 324.

³ F. Smithson, *Geol. Mag.*, lxv., 1928, p. 24.

^{4, 5} Author's observations.

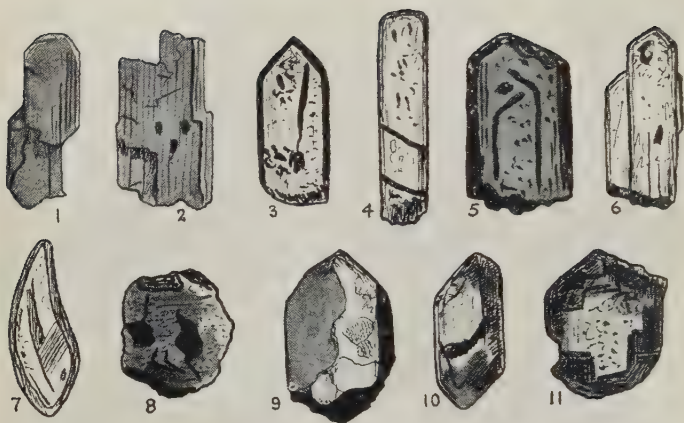


FIG. 49. HYPERSTHENE.

1-3, Sand from Fiji Is.; 4-6, Volcanic Sand, Mont Pelée, Martinique;
 Shore Sand, S.E. Arabia; 8, Recent Sand, Gold Coast, W. Africa; 9-
 Pleistocene Sand, Portugal. [x 25.]

HYPERSTHENE.* [Fig. 49. Pl. XII.]

Chem. Comp. (Mg,Fe)SiO₃.

System. Orthorhombic.

Habit. Prismatic, bipyramidal.

Structure. Crystalline.

Cleavage. Distinct parallel to (110), fair parallel to (100) and (010).

Fracture. Uneven.

Hardness. 5 to 6.

Spec. Grav. 3.4 to 3.5.

Lustre. Vitreous, pearly on cleavage faces.

Colour. Brownish-green, grey-green or olive. Translucent.

Mag. Prop. Weakly magnetic, varies with iron content.

Elect. Prop. Moderate conductor.

Opt. Prop. R.I. high, $\alpha = 1.692$, $\beta = 1.702$, $\gamma = 1.705$.

Birefringence low, $\gamma - \alpha = 0.013$. Optically biaxial, negative. Optic axial plane parallel to (010). $Bxa = X$ normal to (100). Optic axial angle varies with amount of FeO present. $2V = 75^\circ$ (decreases with increase of Fe). Dispersion weak, $\rho > v$. $X \parallel a$, $Y \parallel b$, $Z \parallel c$. Straight extinction. Pleochroism marked in the more ferriferous varieties: X pink, Y yellow, Z green, also birefringence increases.

Characters in Sediments. Not a common mineral in sediments as a rule, but to be anticipated in deposits derived from contiguous hypersthene-bearing igneous rocks. It usually assumes a ragged, prismatic habit and displays characteristic pleochroism, pink, red or brown to green (as above). Grains often full of minute inclusions (Schiller-structure), identified as iron-ore or some form of TiO₂. Detrital hypersthene is usually pale brownish-green to greyish-green in colour, though exceptionally deep brown euhedral varieties occur (with striking green pleochroism) in the vicinity of volcanic lavas. The (110) cleavage is often conspicuous.

Occurrence. " Apart from Scottish occurrences, occasional pleochroic grains have been recorded from the Carboniferous of North Wales, the Permian of Lancashire, the Trias of the Vale of Clwyd, the Middle Lias, Portlandian, Lower Greensand, Headon Beds and London

* For *Enstatite*, the less ferriferous variety of rhombic pyroxene, see p. 173.

Clay."¹ In the Northampton Ironstone (Inferior Oolite);² in the Upper Kimmeridge Clay and Portland Sand of Thame, etc., Bucks;³ in the dune sands of South Wales;⁴ deep brown prisms in superficial deposits, Mont Pelée, Martinique;⁵ in shore sand, Kynance Cove, Cornwall.⁶

Possible Sources of Derivation. Intermediate, basic and ultrabasic igneous rocks, e.g., gabbro (norite), dolerite, basalt and volcanic rocks generally.

REMARKS.—If hypersthene is anticipated in a sample, avoid using strong HCl in cleaning; some varieties are readily attacked by acid, enstatite being more stable in this respect.

¹ P. G. H. Boswell, *Trans. Geol. Soc. Glasgow*, xviii., 1926-27, p. 140.

² J. G. A. Skerl, *Proc. Geol. Assoc.*, xxxviii., 1927, p. 381.

³ E. Neaverson, *Proc. Geol. Assoc.*, xxxvi., 1925, p. 250.

⁴ A. Stuart, *Proc. Geol. Assoc.*, xxxv., 1924, p. 324.

^{5, 6} Author's observations.

ILMENITE.

[Fig. 50.]

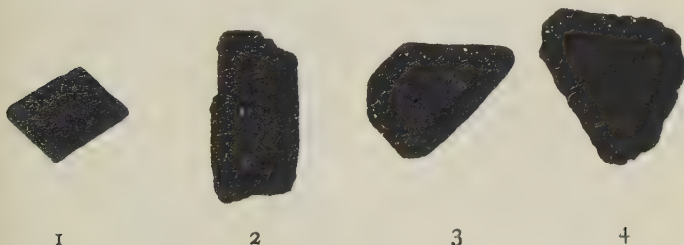
Chem. Comp. FeTiO_3 .*System.* Rhombohedral.*Habit.* Euhedral, tabular parallel to (0001).*Structure.* Crystalline, or in compact platy masses.*Cleavage.* None. Parting sometimes developed in twin crystals.*Fracture.* Conchoidal.*Hardness.* 5 to 6.*Spec. Grav.* 4.5 to 5.*Lustre.* Submetallic, steel-grey, often with crimson or purplish sheen.*Colour.* Iron-black.*Mag. Prop.* Moderately magnetic.*Elect. Prop.* Good conductor.*Opt. Prop.* Opaque, purplish-brown in very thin section.

FIG. 50. Ilmenite.

1-3. Demerara, British Guiana. [x 60.]

4. Alluvials, Ceylon. [x 20.]

Characters in Sediments. Commonly occurring in irregular, subangular grains, with characteristic purple-grey or sometimes crimson submetallic lustre in reflected light. Grains quite opaque in transmitted light. Partial alteration to leucoxene (p. 205) frequently observed, also more rarely secondary out-growths of rutile, anatase. See p. 445.

Occurrence. An ubiquitous species in detrital sediments; far commoner than any other iron-ore, including magnetite. Recorded from deposits of every stratigraphical horizon: Pre-Cambrian to Recent. For alluvial types

see C. Raeburn & H. B. Milner, "Alluvial Prospecting," 1927, p. 398.

Possible Sources of Derivation. Igneous rocks, especially basic and ultrabasic types.

REMARKS. — Ilmenite frequently presents characters which render discrimination between it and associated magnetite a matter of great difficulty under the microscope. Strong artificial incident light may aid its identification, and an initial concentration can also be effected by extracting the magnetite with a powerful horseshoe or bar magnet. Where partial alteration to leucoxene occurs, there is little fear of confusion.

KAOLINITE.

[Fig. 51.]

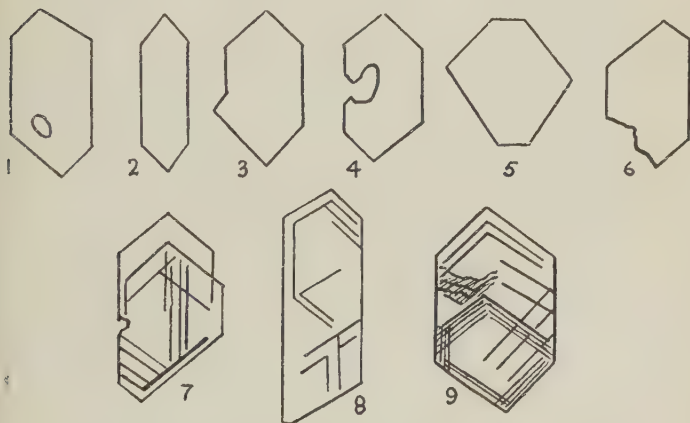
Chem. Comp. $\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$.*System.* Monoclinic.*Habit.* Flattened parallel to (001); pseudo-hexagonal or rhombohedral plates.*Structure.* Commonly amorphous, powdery or in laminated aggregates; more rarely crystalline.*Cleavage.* Perfect basal, parallel to (001).*Fracture.* Irregular.*Hardness.* 2 to 2.5.*Spec. Grav.* 2.6 to 2.63.*Lustre.* Pearly on (001) face, otherwise dull or earthy.*Colour.* White, yellow or brown. Translucent.*Mag. Prop.* Non-magnetic.*Elect. Prop.* Non-conductor.

FIG. 51. Kaolinite from Clay. 1—6, Denver, Colorado,
7—9, Amlwch.

Opt. Prop. R.I. low, 1.563 (mean value). Birefringence low, $\gamma - a = 0.007$ approximately. Optically biaxial, negative. Optic axial plane perpendicular to (010). *Bxo* normal to (010). *Bxa* = *X* inclined at 4° to *c*. $Z \parallel b$. $2V = 68^\circ$ ($90^\circ?$). Dispersion weak, $\rho > \nu$.

Characters in Sediments. Occurs rarely as irregular, colourless aggregates or as pseudo-rhombohedral scaly masses, characteristic of the light material of the sediment. Very perfect euhedra are sometimes obtainable from certain clays: see *fig. 51*.

Occurrence. In clays related to "bentonite," U.S.A.;¹ in Pliocene silts of St. Agnes, Cornwall.²

Possible Sources of Derivation. Altered acid igneous and aluminous rocks. Common alteration product of feldspar; clays.

REMARKS.—Kaolinite may be confused with muscovite, from which it may be distinguished by its lower R.I., birefringence, and by absence of good interference figure (characteristic of mica) in (001) cleavage flakes. It is a mineral easily overlooked.

¹ C. S. Ross & E. V. Shannon, *Journ. Amer. Ceramic Soc.*, ix., 1926, pp. 77-96.

² H. B. Milner, *Q.J.G.S.*, lxxviii., 1922, pp. 357-8.

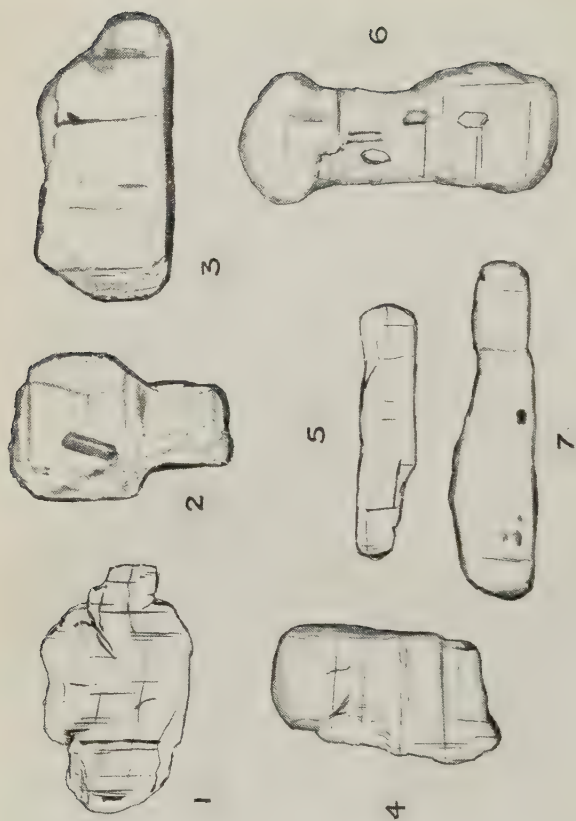


FIG. 52. KYANITE.

1, 7. Lower Greensand, N.W. Wiltshire.

2, 3. Alluvials, West Africa.

4. Hamstead, North London.

KYANITE. [Fig. 52. Pl. XIII.]

Chem. Comp. $\text{Al}_2\text{O}_3 \cdot \text{SiO}_2$.

System. Triclinic.

Habit. Elongated prismatic ("bladed") crystals with irregular terminations. Fibrous.

Cleavage. Perfect parallel to (100), fair parallel to (010), trace parallel to (001). Parting planes parallel to (001), and (308) in twin crystals.

Fracture. Ragged.

Hardness. Varies from 4 to 7 with direction: 4 to 5 on (100) parallel to length of crystal, 7 on (010).

Spec. Grav. 3.559 to 3.675, being higher in coloured varieties.

Lustre. Vitreous, pearly.

Colour. Colourless, white, greyish-green, blue. Transparent.

Mag. Prop. Non-magnetic.

Elect. Prop. Bad conductor.

Opt. Prop. R.I. very high, $\alpha = 1.7171$, $\beta = 1.7222$, $\gamma = 1.7290$. Birefringence low, $\gamma - \alpha = 0.0119$. Optically biaxial, negative. Optic axial plane inclined at 30° to prism-edge (100) (010). $Bxa = X$ almost normal to (100). $2V = 82^\circ - 84^\circ$. Oblique extinction, $\pm 30^\circ$ from (100). Pleochroism slight in deeply coloured varieties: dark to light blue. Dispersion slight, $\rho > v$.

Characters in Sediments. Varies greatly in physical characters, the commonest type being the subangular prismatic grain (100), elongated in the direction of the principal axis, irregularly terminated, and with or without traces of the (001) cleavage at right angles to the length of the grain and (010) cleavage parallel to the prism-margins. A more abraded form is the short "stumpy" grain, usually well rounded and sometimes exhibiting re-entrants due to fracture of the prism face. Compound cleavage fragments, due to differential abrasion of (100) and (010) are often observed, re-entrants in such cases being very marked; these fragments are usually sharply angular. Grains flattened parallel to (010) are rare: they give straight extinction, and do not show the interference figure typical of the (100) grains. Pleochroic grains are extremely rare. Inclusions of carbonaceous matter common. In some of the older sedimentary deposits "shimmer-aggregates" are found; these consist of colourless cores of kyanite surrounded by cryptocrystalline micaceous

material, containing abundant inclusions. Such aggregates are, for the most part, decomposition products of kyanite and allied aluminous silicates. (H. H. Thomas, *Q.J.G.S.*, lviii., 1902, p. 627).

Occurrence. Numerous records in post-Armorican deposits. In Upper Lias-Inferior Oolite, West of England*;¹ in the Northampton Ironstone (refer specially for notes on decomposition);² in the Portland Sand of Dorset*;³ in the Ashdown Sand, Hastings, Sussex;⁴ in the Carstone (Lower Greensand) of Yorkshire and Lincolnshire;⁵ in the Lower Greensand of Norfolk, Bedfordshire, etc.*;⁶ in the Thanet Sands, Reading Beds and London Clay of the N.E. London Basin*;⁷ in the Bagshot Beds of Essex;⁸ in the Pliocene deposits of St. Erth and St. Agnes, Cornwall*;⁹ in the later Tertiary deposits of the East of England;¹⁰ in the dune sands of South Wales.¹¹ (N.B.—Occurrences denoted * are figured in the appropriate references below).

Possible Sources of Derivation. Metamorphic rocks, especially mica schists and certain gneisses.

REMARKS.—Owing to the variety of forms presented by this mineral in sediments, it is a valuable species for correlation purposes, since detailed study shows that certain types are characteristic of definite horizons. Kyanite frequently affords direct evidence of the source of origin of the material in which it occurs, and by the degree of abrasion suffered it may signify the nature and potency of the transporting medium. It is found associated with garnet, staurolite, andalusite and corundum in many instances, both in metamorphic rocks and in relevant detrital sediments.

¹ P. G. H. Boswell, *Geol. Mag.*, lxi., 1924, pp. 254-5.

² J. G. A. Skerl, *Proc. Geol. Assoc.*, xxxviii., 1927, p. 384.

³ M. P. Latter, *Proc. Geol. Assoc.*, xxxvii., 1926, p. 84.

⁴ H. B. Milner, *Proc. Geol. Assoc.*, xxxvi., 1925, p. 315.

⁵ H. C. Versey & C. Carter, *Proc. Yorks. Geol. Soc.*, xx., 1926, pp. 349-365.

⁶ R. H. Rastall, *Geol. Mag.*, 1919, pp. 214, 271.

⁷ P. G. H. Boswell, *Q.J.G.S.*, lxxi., 1915, pp. 577, 579, & pl. xlvii.

⁸ S. W. Wooldridge, *Proc. Geol. Assoc.*, xxxv., 1924, p. 379.

⁹ H. B. Milner, *Q.J.G.S.*, lxxviii., 1922, p. 371.

¹⁰ I. S. Double, *Proc. Geol. Assoc.*, xxxv., 1924, pp. 342-3.

¹¹ A. Stuart, *Proc. Geol. Assoc.*, xxxv., 1924, p. 325.

LEPIDOLITE.

Chem. Comp. $2\text{H}_2\text{O} \cdot \text{K}_2\text{O} \cdot \text{Li}_2\text{O} \cdot 2\text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2$. (Hallimond).

System. Monoclinic.

Habit. Tabular parallel to (001) with pseudo-hexagonal or irregular outline; sometimes elongated. Twinning about plane perpendicular to (001) common: contact plane (001).

Structure. Crystalline, laminated.

Cleavage. Highly perfect parallel to (001). Parting parallel to (010) and ($\bar{1}11$). Parting and gliding planes parallel to various crystal faces produced by percussion (see Iddings, *Rock Minerals*, 1906, p. 419).

Fracture. Irregular but rarely seen.

Hardness. 2.5 to 4.

Spec. Grav. 2.8 to 2.9.

Lustre. Vitreous to pearly.

Colour. Lilac to mauve, white, yellow, grey, pink. Transparent.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. moderately high, $\alpha = 1.5600$, $\beta = 1.5975$, $\gamma = 1.6047$. Birefringence strong, $\gamma - \alpha = 0.047$. Optically biaxial, negative. Optic axial plane normal to (010). Bxa nearly normal to cleavage plane (001), hence most flakes yield good interference figure. $2E$ varies from $57^\circ 10'$ to $84^\circ 1'$; $2V = \pm 40^\circ$. Pseudo-uniaxial varieties are also noted. Sometimes distinctly pleochroic: Y and Z lilac or pink, X colourless. Dispersion, $\rho > \nu$.

Characters in Sediments. Occurs much as muscovite does, in irregular cleavage flakes, but of characteristic lilac to mauve colour. The refractive index is higher than that of muscovite, and the birefringence is also higher. Intimate association with muscovite (zonal structure) in the same flake may be sometimes noted. Inclusions are usually absent, a further point of distinction from white mica.

Occurrence. Hitherto unrecorded from British sediments. Mauve-coloured mica flakes are noted from time to time

in sands, *e.g.*, shore sands of East Anglia, which may be referable to this species. Not uncommon in some of the late Tertiary sands of the Los Angeles basin, S. California, U.S.A.¹

Possible Sources of Derivation. Granite, pegmatite.

REMARKS. — Lepidolite is to some extent attacked by hydrochloric acid, so that flakes may show etching or apparent alteration due to the initial cleaning of the sediment. Muscovite is not thus affected.

- Author's observations.

LEUCOXENE. [Fig. 53. Pl. XIV.]

Chem. Comp. A decomposition product of ilmenite, as yet ill-defined. It is probably for the most part a form of titanite (p. 244), with possibly some carbonate. It has been described by Iddings as a form of anatase or perovskite.

System. Non-crystalline.

Habit. Irregular aggregates or as pseudomorphs after ilmenite.

Structure. Amorphous.

Spec. Grav. Varies from 3.5 to 4.5.

Lustre. Dull.

Colour. White, yellow or brown. Translucent to opaque.

Mag. Prop. Non-magnetic.

Elect. Prop. Moderate conductor.

Opt. Prop. High R.I., and birefringence, seen in translucent flakes.

Characters in Sediments. Commonly occurs as rounded grains, opaque in transmitted light, white or yellowish-white in reflected light, having an "unglazed porcelain" appearance. Sometimes a core of unaltered ilmenite may be observed, in which case the grain will appear weakly magnetic. A rough "pitted" surface is characteristic of most grains, best seen by reflected light. Where the mineral is reasonably translucent, aggregate polarisation may be observed with crossed nicols.

Occurrence. Ubiquitous in detrital sediments as with ilmenite (p. 197).

Possible Sources of Derivation. Essentially from ilmenite, and largely *in situ*.

LIMONITE.

Chem. Comp. $2\text{Fe}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$.

System. Non-crystalline.

Habit. Varied; pseudomorphous after iron-ores.

Structure. Amorphous, earthy.

Fracture. Uneven.

Hardness. 5.5.

Spec. Grav. 3.8.

Lustre. Submetallic, dull.

Colour. Dark brown, yellowish-brown.

Mag. Prop. Varies according to degree of alteration of the original mineral from which it was derived; essentially non-magnetic *per se*.

Elect. Prop. Moderate conductor.

Opt. Prop. Opaque.

Characters in Sediments. Of frequent occurrence as irregular grains and as powdery aggregates. It has a brown, ocherous colour by reflected light, being opaque in transmitted light except in very thin sections, when a brownish-yellow colour prevails. The translucent particles are isotropic. Limonitic pseudomorphs after marcasite, pyrite, magnetite and hæmatite are not uncommon, while its occurrence as a decomposition product of glauconite is often observed. It represents one of the most prevalent forms of authigenous material found in sediments.

Occurrence. Ubiquitous in detrital sediments as a cementing medium.

Possible Sources of Derivation. Iron-ores of varying composition. Iron-bearing minerals.

REMARKS. — Limonite is the commonest coating of detrital particles, and its removal, prior to their microscopical analysis, necessitates the usual preliminary treatment of a sample with dilute HCl or alkali.

MAGNETITE.

[Fig. 54.]

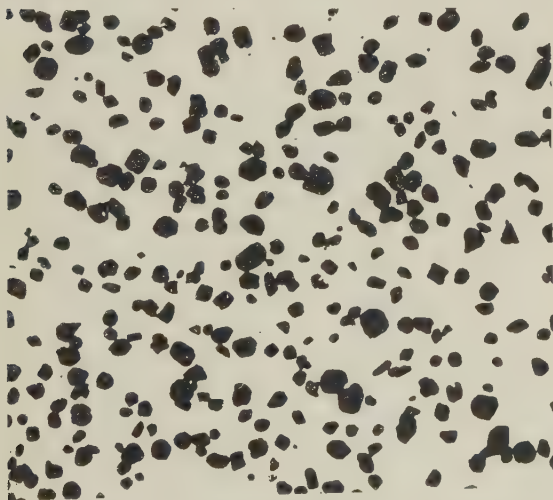
Chem. Comp. Fe_3O_4 .*System.* Cubic.*Habit.* Octahedral, dodecahedral (sometimes with striations parallel to major diagonal of crystal face), or twinned on (111).*Structure.* Crystalline, granular, massive.*Cleavage.* None. Parting parallel to (111).*Fracture.* Subconchoidal, uneven, hackly.*Hardness.* 5.5 to 6.5.*Spec. Grav.* 5.168 to 5.180.*Lustre.* Metallic, submetallic, dull.*Colour.* Silver-grey.*Mag. Prop.* Strongly magnetic.*Elect. Prop.* Good conductor.*Opt. Prop.* Opaque.*Characters in Sediments.* The octahedral, silver-grey or black crystals of this species are very characteristic, as also are the irregular shaped, shiny black grains. Careful examination of some grains with powerful inci-

FIG. 54. Magnetite, Alluvial Sand, Colombia, S. America. [x 20.]

dent light and high power objective frequently reveals the presence of minute facets. In the absence of such faceting, the grains may have only a dull grey lustre, and be difficult to distinguish from ilmenite (p. 198). Both angular and well rounded irregular grains are also common, the former often showing a marked hackly fracture. Partial alteration to limonite is frequently observed.

Occurrence. Numerous records extant. The following examples have been confirmed with the bar or electromagnet and are so recorded by the authors concerned:—in the Upper Lias—Inferior Oolite, West of England;¹ in the Pliocene deposits of Cornwall;² in the later Tertiary deposits of East of England.³ Other occurrences are:—in the Old Red Sandstone of the West Midlands;⁴ in the Northampton Ironstone;⁵ in the dune sands of South Wales;⁶ in the Dartmoor detritals.⁷

Possible Sources of Derivation. Basic and ultrabasic igneous rocks.

REMARKS.—Less common in sediments than ilmenite. Distinguished from ilmenite by its lustre and crystalline form if developed, and may be separated from that mineral by using a horseshoe or bar magnet, which is always the safest preliminary test in diagnosis.

¹ P. G. H. Boswell, *Geol. Mag.*, lxi., 1924, p. 253.

² H. B. Milner, *Q.J.G.S.*, lxxviii., 1922, pp. 354, 358.

³ I. S. Double, *Proc. Geol. Assoc.*, xxxv., 1924, p. 338.

⁴ W. F. Fleet, *Geol. Mag.*, lxiii., 1926, p. 513.

⁵ J. G. A. Skerl, *Proc. Geol. Assoc.*, xxxviii., 1927, p. 379.

⁶ A. Stuart, *Proc. Geol. Assoc.*, xxxv., 1924, p. 321.

⁷ A. Brammall, *Proc. Geol. Assoc.*, xxxix., 1928, p. 35.

MARCASITE.

Chem. Comp. FeS_2 .

System. Orthorhombic.

Habit. Commonly twinned, simple crystals rare.

Structure. Crystalline, fibrous, concretionary and radiating.

Cleavage. Poor parallel to (110), imperfect parallel to (011).

Fracture. Uneven, ragged. (Very brittle.)

Hardness. 6.

Spec. Grav. 4.8.

Lustre. Metallic, splendent.

Colour. Brass-yellow to greyish-yellow.

Mag. Prop. Weakly magnetic.

Elect. Prop. Good conductor.

Opt. Prop. Opaque.

Characters in Sediments. Grains usually small, very ragged and possessing a typical greyish-yellow metallic lustre in reflected light; superficial alteration to limonite is commonly shown. Traces of radial structure noted in some examples.

Occurrence. In the Sandgate Beds (Lower Greensand), Gault, Chalk, Woolwich and Reading Beds, and London Clay of the Croydon Regional Survey area (Surrey, etc.);¹ in the Thanet Beds, Reading Beds and London Clay, N.E. London Basin.²

Possible Sources of Derivation. Metalliferous veins; sedimentary rocks, especially chalk.

REMARKS.—Much less common than its isomer pyrite, being easily decomposed. Molluscan fragments preserved in marcasite sometimes found.²

¹ G. M. Davies, *Proc. and Trans. Croydon Nat. Hist. Soc.*, 1915-16, p. 86.

² P. G. H. Boswell, *Q.J.G.S.*, lxxi., 1915, pp. 577, 581, & table iv.

MICROCLINE. [Fig. 55. Pl. XIV.]

Chem. Comp. $K_2O \cdot Al_2O_3 \cdot 6SiO_2$.

System. Triclinic.

Habit. Prismatic, frequently twinned.

Structure. Crystalline, massive.

Cleavage. Distinct parallel to (001), imperfect parallel to (010), more rarely parallel to (110) and ($\bar{2}01$). Parting parallel to (100) occasionally seen.

Fracture. Conchoidal, uneven.

Hardness. 6 to 6.5.

Spec. Grav. 2.54 to 2.57.

Lustre. Vitreous.

Colour. White, yellow, green or red.

Mag. Prop. Non-magnetic.

Elect. Prop. Bad conductor.

Opt. Prop. R.I. low, $\alpha = 1.5224$, $\beta = 1.5264$, $\gamma = 1.5295$.

Birefringence low, $\gamma - \alpha = 0.0071$. Optically biaxial, negative. Optic axial plane nearly perpendicular to (010). Bxa inclined at small angle ($< 5^\circ$) to axis a . $2V = 83^\circ$. (001) flakes give oblique extinction, 16° , and (010) flakes give 5° , measured from the trace of (010) and (001) cleavages respectively. (001) plates invariably show characteristic "cross-hatched" structure, due to combination of albite and pericline twinning.

Characters in Sediments. "Platy" basal grains (001) are the most common, easily recognized by the characteristic "cross-hatching" in polarised light. Other forms, such as (010) cleavage fragments, are rarer. In most examples the grains present irregular outlines. Inclusions are sometimes seen; these may be primary muscovite (distinct from that occurring as a decomposition product), zircon, iron-ores or quartz. Decomposition to muscovite or kaolinite renders grains greyish-white by reflected light, and causes the appearance of highly polarising aggregates between crossed nicols.

Occurrence. In the Torridon Sandstone of N.W. Highlands and of S.E. Skye, N.B.;¹ in the Malvern quartzite;² in the Old Red Sandstone, Cardiff district;³ in

¹ Author's observations; see also *Mem. Geol. Surv. Scot.*, N.W. Highlands, 1907, ch. xvi.

² G. S. Sweeting, *Proc. Geol. Assoc.*, xxxviii., 1927, p. 551.

³ A. Heard & R. Davies, *Q.J.G.S.*, lxxx., 1924, p. 508.

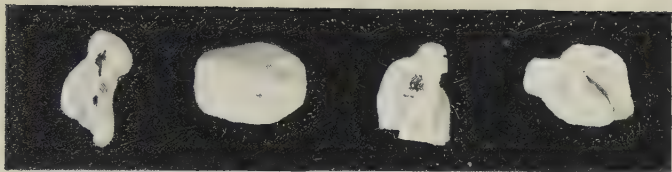


FIG. 53. LEUCOXENE.
Upper Eocene, Auvers-sur-Oise, nr. Paris. [x 40.]

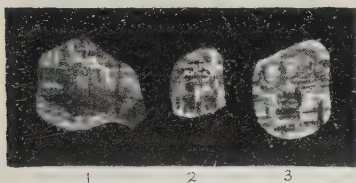


FIG. 55. MICROCLINE (x *Nicols*).
1, 2. Torridon Sandstone, Skye, N.B. [x 40.] 3. Abbotsbury Iron Ore
(Corallian), Abbotsbury, Dorset. [x 40.]

the Old Red Sandstone, West Midlands;¹ in the Millstone Grit, Yorkshire;² in the Middle Permian sands of Yorkshire;³ in the New Red Sandstone, West of England;⁴ in the Northampton Ironstone;⁵ in the Abbotsbury Iron-Ore (Corallian) Dorset;⁶ in the later Tertiary deposits, East of England;⁷ in surface deposits of S.E. Devon.⁸

Possible Sources of Derivation. Acid igneous rocks. Metamorphic rocks.

REMARKS.—Anorthoclase, the soda-microcline, has been observed occasionally as loose grains. Characterized by irregular "patchy" intergrowth; R.I. 1.52. (I. S. Double, *loc. cit. infra*.)

¹ W. F. Fleet, *Geol. Mag.*, lxiii., 1926, p. 512.

² A. Gilligan, *Q.J.G.S.*, lxxv., 1919, p. 262.

³ H. C. Versey, *Proc. Yorks. Geol. Soc.*, xx., 1925, p. 205.

⁴ H. H. Thomas, *Q.J.G.S.*, lxv., 1909, p. 239.

⁵ J. G. A. Skerl, *Proc. Geol. Assoc.*, xxxviii., 1927, p. 385.

⁶ Author's observations.

⁷ I. S. Double, *Proc. Geol. Assoc.*, xxxv., 1924, p. 336.

⁸ W. G. Shannon, *Geol. Mag.*, lxiv., 1927, p. 148.

General Reference.

Harold L. Alling, "The Mineralography of the Feldspars," *Journ. Geol.*, xxxi., 1923, pp. 282-305, 353-375. See also Bibliography, under "Mackie" (p. 495).

MONAZITE. [Fig. 56. Pl. XV.]

Chem. Comp. (Ce,La,Nd,Pr)PO₄.

System. Monoclinic.

Habit. Small crystals flattened parallel to (100) with varying terminations.

Structure. Crystalline, granular.

Cleavage. Perfect parallel to (001), good parallel to (100), less commonly parallel to (010), rarely parallel to ($\bar{1}11$).

Fracture. Uneven, conchoidal.

Hardness. 5 to 5.5.

Spec. Grav. 4.9 to 5.3.

Lustre. Vitreous, resinous.

Colour. Yellow, yellowish-brown, red. Translucent to opaque.

Mag. Prop. Weakly magnetic.

Elect. Prop. Bad conductor.

Opt. Prop. R.I. high, $\alpha = 1.7957$, $\beta = 1.7965$, $\gamma = 1.8411$.

Birefringence high, $\gamma - \alpha = 0.0454$. Optically biaxial, positive. Optic axial plane perpendicular to (010), almost parallel to (100). $Bxa = Z$ inclined to principal axis at angle of 4° . $X = b$. $2E = 24^\circ$. $2V = 13^\circ - 15^\circ$. Pleochroism seen in thick grains: X light yellow to Z greenish-yellow. Absorption: $Y > Z = X$. Dispersion weak, $\rho < \nu$.

Characters in Sediments. Usually occurring as well rounded, pale yellow grains with dark border, due to R.I. effect. Colourless, or by contrast, deep brown, almost opaque grains met with. The common detrital form is the rounded, egg-shaped crystal derived from faceted tablets parallel to (100); perfect euhedra, sometimes strongly faceted, are met with; (001) cleavage fragments are also frequent: these yield a good positive interference figure. Brammall has described and figured octagonal, hexagonal, quadrilateral and heptagonal crystal habits from the Dartmoor detritals. Decomposition often noted superficially in the form of brown coloured patches or stains which are probably complex alteration products of cerium, etc. Inclusions often noted, chiefly gas-filled cavities. Brammall states that "Suspensions of opaque dust or brown-red stains are of occasional occurrence; crystalline inclusions are rare."¹

¹ Ref. ⁹, p. 213.

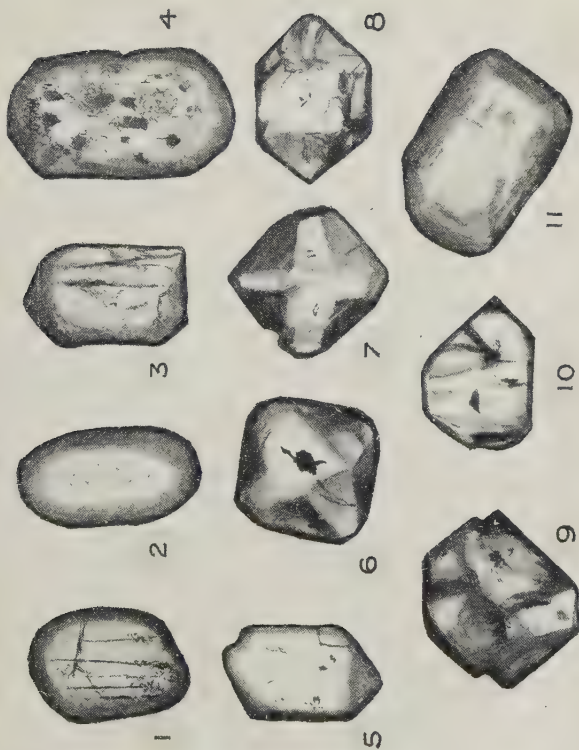


FIG. 56. MONAZITE.

- 1, 2. Recent Sands, Cape Comorin, Travancore, India. [x 70.]
 3-5. Recent Sands, Ceylon. [x 40.]
 6-11. Alluvials, Brazil. [x 70.]

Occurrence. In the Millstone Grit of Yorkshire;¹ in the Northampton Ironstone;² in the Ashdown Sands and Fairlight Clays (Wealden) of the Hastings district, Sussex;³ in the Lower Greensand of Surrey;⁴ in the Eocene (?) of Buckland Brewer, and the Oligocene of the Bovey Basin, Devonshire;⁵ in the Lenham Beds of Kent, etc.;⁶ in the valley deposits derived from the Chipstead and Headley Sands, Surrey;⁷ in Glacial deposits of the Dublin district;⁸ in the Dartmoor detritals.⁹

Possible Sources of Derivation. Acid igneous rocks, especially granites.

REMARKS. There may be a little difficulty in recognizing monazite under the microscope, and if necessary confirmation may be obtained both chemically and spectroscopically. In the former case the phospho-molybdate reaction is sought, and in the latter case the absorption spectrum with the characteristic neodymium-praseodymium bands is easily identified. The use of a spectroscopic eyepiece attachment to the petrological microscope facilitates this observation.

¹ A. Gilligan, *Q.J.G.S.*, lxxv., 1919, p. 267.

² J. G. A. Skerl, *Proc. Geol. Assoc.*, xxxviii., 1927, p. 383.

³ H. B. Milner, *Proc. Geol. Assoc.*, xxxvi., 1925, p. 315.

⁴ G. M. Davies, *Proc. Croydon Nat. Hist. Soc.*, 1915-16, p. 93.

⁵ P. G. H. Boswell, *Q.J.G.S.*, lxxix., 1923, p. 226.

⁶ G. M. Davies, quoted by P. G. H. Boswell: see *gen. ref.* below.

⁷ G. M. Davies, *op. cit.*

⁸ F. Smithson, *Geol. Mag.*, lxv., 1928, p. 24.

⁹ A. Brammall, *Proc. Geol. Assoc.*, xxxix., 1928, pp. 29-30.

General References.

C. Raeburn & H. B. Milner, "Alluvial Prospecting," 1927, pp. 405-6 (for alluvial occurrences, "monazite sands," etc.).

F. W. Clarke, "Data of Geochemistry," *U.S.G.S.*, Bull. 770, 5th ed., 1924, p. 359.

P. G. H. Boswell, *Trans. Geol. Soc. Glasgow*, xviii., 1926-27, pp. 137-8.

MUSCOVITE. [Fig. 57. Pl. XVI.]

Chem. Comp. $H_2KAl_3(SiO_4)_3$.

System. Monoclinic.

Habit. Tabular crystals, parallel to (001). Pseudo-orthorhombic or pseudo-rhombohedral forms found.

Structure. Well laminated, massive; individual crystals rare.

Cleavage. Extremely perfect parallel to (001). Parting parallel to (010) and ($\bar{1}11$).

Fracture. Ragged (rare).

Hardness. 2 to 2.5.

Spec. Grav. 2.76 to 3.

Lustre. Vitreous, pearly.

Colour. Colourless to yellow, deepening with thickness.

Mag. Prop. Normally non-magnetic, occasionally magnetic.

Elect. Prop. Bad conductor.

Opt. Prop. R.I. low, $\alpha = 1.5609$, $\beta = 1.5941$, $\gamma = 1.5997$.

Birefringence high, $\gamma - \alpha = 0.0388$, but that usually seen in cleavage (001) flakes is due to $\gamma - \beta = 0.0056$, and hence is very low. Optically biaxial, negative. Optic axial plane is normal to (010). $Bxa = X$ practically normal to (001), hence cleavage plates always yield good figure, $2V = \pm 40^\circ$. $Z = b$. Dispersion, $\rho > \nu$.

Characters in Sediments. Commonly in thin, colourless platy grains (001), with characteristic low R.I., bluish-grey interference tint and good figure. Other forms extremely rare. Grains usually rounded and often from three to four times larger than the average grade-size of associated minerals. Inclusions are common, such as zircon, rutile, tourmaline and garnet. Undulose extinction is a feature of some varieties, implying derivation from metamorphic rocks.

Occurrence. In the Torridonian, S.E. Skye, N.B.;¹ in the Hollybush Sandstone (Cambrian) of the Malvern district;² in Cambrian shales, Ordovician and Silurian sands, Lower Devonian sandstone of the English Midlands;³ in the May Hill Sandstone (Silurian) of the Malvern district;⁴ in the Downtonian of the West Mid-

¹ Author's observations.

² G. S. Sweeting, *Proc. Geol. Assoc.*, xxxviii., 1927, p. 553.

³ W. F. Fleet, *Geol. Mag.*, lxii., 1925, p. 98 *et seq.*

⁴ G. S. Sweeting, *op. cit.*, p. 557.

lands;¹ in the Old Red Sandstone of the Cardiff district;² in the Millstone Grit of Yorkshire;³ in the Bunter Pebble Bed of the West of England;⁴ in the Keuper Waterstones of Leicestershire;⁵ in the Upper Lias—Inferior Oolite sands of the West of England;⁶ in the Kelloways Rock (Oxfordian) of Yorkshire, etc.;⁷ in the Upper Kimmeridge Clay—Portland Sand of Bucks, etc.;⁸ in the Thanet, Reading Beds and London Clay of the N.E. London basin;⁹ in the Pliocene deposits of Cornwall;¹⁰ in the later Tertiary deposits of the East of England;¹¹ in the Dartmoor detritals.¹²

Possible Sources of Derivation. Igneous and metamorphic rocks.

REMARKS.—It is sometimes found that two distinct varieties of muscovite occur in a sediment, one which floats, the other which sinks in bromoform (S.G. 2.9). In such circumstances very careful optical examination of the grains is desirable and may lead to the suspicion of leached biotite in the case of the heavier flakes.

¹ W. F. Fleet, *Geol. Mag.*, lxiii., 1926, p. 512

² A. Heard & R. Davies, *Q.J.G.S.*, lxxx., 1924, p. 499.

³ A. Gilligan, *Q.J.G.S.*, lxxv., 1919, p. 263.

⁴ H. H. Thomas, *Q.J.G.S.*, lviii., 1902, p. 626.

⁵ T. O. Bosworth, "Keuper Marls around Charnwood," Leicestershire, *Leicester Lit. & Phil. Soc.*, p. 93.

⁶ P. G. H. Boswell, *Geol. Mag.*, lxi., 1924, p. 252.

⁷ Author's observations.

⁸ E. Neaverson, *Proc. Geol. Assoc.*, xxxvi., 1925, p. 251.

⁹ P. G. H. Boswell, *Q.J.G.S.*, lxxi., 1915, pp. 576, 578, 581.

¹⁰ H. B. Milner, *Q.J.G.S.*, lxxviii., 1922, p. 358.

¹¹ I. S. Double, *Proc. Geol. Assoc.*, xxxv., 1924, p. 341.

¹² A. Brammall, *Proc. Geol. Assoc.*, xxxix., 1928, p. 46.

OLIVINE. [Fig. 59. Pl. XVI.]

Chem. Comp. $(\text{Mg,Fe})_2\text{SiO}_4$.

System. Orthorhombic.

Habit. Flattened prismatic crystals parallel to (100) or (010) with bipyramidal and basal terminations.

Structure. Crystalline.

Cleavage. Poor parallel to (010) and (100).

Fracture. Conchoidal.

Hardness. 6.5 to 7.

Spec. Grav. 3.27 to 3.37.

Lustre. Vitreous, resinous.

Colour. Green, olive green, dark green, brown.

Mag. Prop. Weakly magnetic.

Elec. Prop. Bad conductor.

Opt. Prop. R.I. high, $\alpha = 1.6720$, $\beta = 1.6899$, $\gamma = 1.7089$.

Birefringence high, $\gamma - \alpha = 0.0369$. Optically biaxial, positive or negative. Optic axial plane parallel to (001). $Bxa = Z$, or with $>12\%$ $\text{FeO} = X$, either normal to (100) or (010) according to amount of FeO present; in former case crystal is positive, in the latter case it is negative. $X \parallel b$, $Y \parallel c$, $Z \parallel a$. Non-pleochroic. Grains elongated parallel to principal axis give straight extinction. Dispersion, $\rho < \nu$.

Characters in Sediments. Usually occurs as irregular and much fractured grains, showing traces of decomposition to serpentine along one or more prominent cracks, which may also be accentuated by iron oxide. Well preserved euhedra sometimes met with (fig. 59, 1). The normal colour tends to be bleached to a yellowish-green tint. Grains are often derived parallel to (100), and frequently show positive biaxial interference figure, with large optic axial angle. Note vivid polarisation colours.

Occurrence. In shore sand, Cape Verde Islands (beautiful euhedra);¹ in shore sand, Kynance Cove, S. Cornwall.²

Possible Sources of Derivation. Basic and ultrabasic igneous rocks: gabbros, dolerites, peridotites, etc.

REMARKS.—A comparatively rare detrital mineral, usually found in recent deposits (such as shore sands or dune sands) occurring in the vicinity of ultrabasic rock masses.

¹ G. M. Part's observations.

² Author's observations.

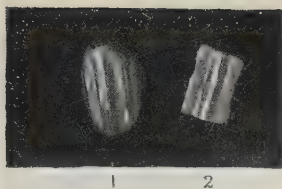


FIG. 57. MUSCOVITE.

1, 2. Kelloways Rock,
near Malton, Yorks. [x 65.]

FIG. 58. PLAGIOCLASE (x *Nicols*).

1. Torridon Sandstone, Skye, N.B. [x 30.]
2. Abbotsbury Iron Ore (Corallian),
Abbotsbury, Dorset [x 30.]

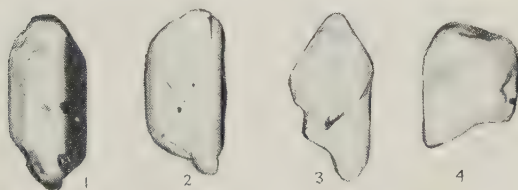


FIG. 59. OLIVINE.

1-4. Shore Sand, Cape Verde Is. [x 35.]

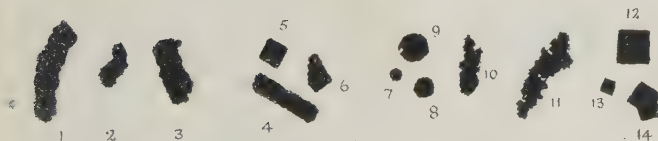


FIG. 60. PYRITE.

1-3. Wadhurst Clay, Southborough, Kent. [x 35.]
4-6. Miocene Clay, Trinidad, B.W.I. [x 35.]
7-10. Middle Lias Ironstone, Cleveland, Yorkshire. [x 35.]
11. Corallian Clay, Weymouth, Dorset. [x 35.]
12-14. Weald Clay, Groombridge, Sussex. [x 35.]

ORTHOCLASE.

Chem. Comp. $K_2O.Al_2O_3.6SiO_2$.

System. Monoclinic.

Habit. Prismatic, often twinned (Carlsbad [001] or Baveno (021)).

Structure. Crystalline.

Cleavage. Perfect parallel to (001), good parallel to (010), imperfect parallel to (110).

Fracture. Conchoidal.

Hardness. 6 to 6.5.

Spec. Grav. 2.54 to 2.56.

Lustre. Vitreous.

Colour. Colourless, grey or reddish-white.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. low, $\alpha = 1.5190$, $\beta = 1.5237$, $\gamma = 1.5260$.

Birefringence low, $\gamma - \alpha = 0.0070$. Optically biaxial, negative. Optic axial plane normal to (010). $B_{\lambda\lambda}$ inclined at 85° to normal of (001). Y or $Z = b$. $2V = 0^\circ - 70^\circ$. (001) plates show straight extinction, (010) plates give extinction angle of 5° .

Characters in Sediments. Irregularly shaped grains flattened parallel to (001) are the usual types met with in the "lighter" portions of clastic sediments. Secondary muscovite or kaolinite clouding the grains is a common feature and in these types aggregate polarisation will usually be noted. Rectangular grains showing definite Carlsbad twinning are sometimes met with; these are accordingly easy to diagnose. Distinction from quartz, where such twinning is absent, is sometimes a matter of difficulty, but R.I. test ($<$ Canada balsam) is usually positive. Inclusions common, quartz, mica, iron-ores, rutile and zircon being observed.

Occurrence. In the Torridonian Sandstones of the N.W. Highlands of Scotland;¹ of S.E. Skye;² in the May Hill Sandstone (Silurian), Malvern district;³ in the Old Red Sandstone of the West Midlands;⁴ of the

¹ J. J. H. Teall, "Geology of N.W. Highlands," *Mem. Geol. Surv., Scot.*, 1907, ch. xvi., p. 278, *et seq.*

² Author's observations.

³ G. S. Sweeting, *Proc. Geol. Assoc.*, xxxviii., 1927, p. 557.

⁴ W. F. Fleet, *Geol. Mag.*, lxiii., 1926, p. 512.

Cardiff district;¹ in the Millstone Grit of Yorkshire;² in the Upper Lias—Lower Inferior Oolite of the West of England;³ in the Reading Beds (Eocene) of the N.E. London Basin;⁴ in the Eocene of Haldon and the Oligocene sands of Bovey Tracey, Devonshire;⁵ in the Pliocene of Cornwall;⁵ in deposits of doubtful age, Lustleigh Cleave, Devonshire (in which the mineral is recorded as “ultradominant”);⁵ in the dune sands of South Wales;⁶ in the Dartmoor detritals.⁷

Possible Sources of Derivation. Acid igneous rocks, pegmatite veins.

REMARKS.—For Anorthoclase, see under Microcline, p. 211.

¹ A. Heard & R. Davies, *Q.J.G.S.*, lxxx., 1924, p. 511.

² A. Gilligan, *Q.J.G.S.*, lxxv., 1919, p. 262.

³ P. G. H. Boswell, *Geol. Mag.*, lxi., 1924, p. 258.

⁴ P. G. H. Boswell, *Q.J.G.S.*, lxxi., 1915, p. 579 & table iv.

⁵ P. G. H. Boswell, *Q.J.G.S.*, lxxix., 1923, p. 226.

⁶ A. Stuart, *Proc. Geol. Assoc.*, xxxv., 1924, p. 324.

⁷ A. Brammall, *Proc. Geol. Assoc.*, xxxix., 1928, p. 46.

General Reference.

Harold L. Alling, “The Mineralography of the Feldspars,” *Journ. Geol.*, xxxi., 1923, pp. 282-305, 353-375. See also Bibliography under “Mackie” (p. 495).

PICOTITE.

Chem. Comp. $(\text{Mg}, \text{Fe})\text{O}, (\text{Al}, \text{Fe}, \text{Cr})_2\text{O}_3$.

System. Cubic.

Habit. Octahedral, irregular, granular.

Structure. Crystalline.

Fracture. Conchoidal.

Hardness. 8.

Spec. Grav. 4.08.

Lustre. Vitreous to dull metallic.

Colour. "Coffee-brown," yellowish-brown or greenish brown. Translucent, sometimes opaque.

Mag. Prop. Moderately magnetic.

Elect. Prop. Good conductor.

Opt. Prop. R.I. high, $n=2.05$. Opaque or exhibiting a greenish-brown translucency, when isotropism is noted.

Characters in Sediments. Usually occurring as rolled octahedral grains of dark but characteristic "coffee" colour, much resembling chromite, from which it is not always easily distinguishable microscopically.

Occurrence. Reading Beds (Lower Eocene) of the London Basin;¹ in the shore sands of Mullion Cove and elsewhere along the West coast of the Lizard, Cornwall (proximity to serpentine masses).²

Possible Sources of Derivation. Similar to chromite: basic and ultrabasic igneous rocks, especially serpentines; crystalline schists.

REMARKS.—As might be expected, picotite as a detrital mineral is of very restricted occurrence; it is practically confined to localized (geologically) recent deposits.

¹ P. G. H. Boswell, *Q. J. G. S.*, lxxi., 1915, p. 578.

² Author's observations.

PLAGIOCLASE. [Fig. 58. Pl. XVI.]

Chem. Comp. Isomorphous group of feldspars varying from Albite ($\text{Na}_2\text{O}.\text{Al}_2\text{O}_3.6\text{SiO}_2$) to Anorthite ($\text{CaO}.\text{Al}_2\text{O}_3.2\text{SiO}_2$).

System. Triclinic.

Habit. Tabular, prismatic, commonly twinned on either Albite law (010), Pericline law (about b axis), Carlsbad law (about c axis), Baveno law (021) or Manebach law (001).

Structure. Crystalline, massive.

Cleavage. Perfect parallel to (001), imperfect parallel to (010), rarely parallel to (110). Parting parallel to (100).

Fracture. Conchoidal, irregular.

Hardness. 6 to 6.5.

Spec. Grav. 2.605 (Albite) to 2.765 (Anorthite).

Lustre. Vitreous, pearly.

Colour. Colourless, grey, greyish-white.

Mag. Prop. Non-magnetic.

Elect. Prop. Bad conductors.

Opt. Prop. R.I. low, (Albite) $\alpha = 1.5290$, $\beta = 1.5333$, $\gamma = 1.5386$; (Anorthite) $\alpha = 1.5752$, $\beta = 1.5833$, $\gamma = 1.5884$. Birefringence low, (Albite) $\gamma - \alpha = 0.0096$, (Anorthite) $\gamma - \alpha = 0.0132$. Optical properties vary with composition, albite being biaxial, positive, and anorthite biaxial, negative. Extinction oblique, varying in (001) grains from 4° in albite to 37° in anorthite, and in (010) grains from 18° in albite to 36° in anorthite.

Characters in Sediments. Grains characterized by irregular outline, presence of twin lamellæ and superficial decomposition products such as muscovite in case of albite feldspar, and saussurite in case of anorthite feldspar. Distinction between various intermediate members of the group is in most cases impossible with single grains unless very definite crystal faces yielding recognizable optical criteria are shown; the R.I. is frequently a clue, being lower than Canada balsam for albite and oligoclase, and higher for andesine, labradorite, bytownite and anorthite; the three latter varieties are, however, very rare as detrital grains. Decomposition products often mask optical characters and multiple twin lamellæ, e.g., mica, kaolinite, when aggregate polarisation is observed. Inclusions common, quartz, iron-ores, zircon, etc. Zoning observed.

Occurrence. In the Torridonian Sandstone of the N.W. Highlands, Scotland (oligoclase),¹ and of S.E. Skye (albite, oligoclase);² in the Malvern quartzite (Cambrian);³ in the May Hill Sandstone (Silurian) of the Malvern district ("minute plagioclase microliths");⁴ in the Old Red Sandstone of the West Midlands,⁵ and of the Cardiff district (oligoclase and oligoclase-andesine);⁶ in the Millstone Grit of Yorkshire (oligoclase);⁷ in the Keuper Marls of Charnwood, Leicestershire;⁸ in the New Red Sandstone of the West of England (perthitic intergrowths of feldspar);⁹ in the Upper Lias—Lower Inferior Oolite of the West of England (oligoclase);¹⁰ in the Northampton Ironstone (oligoclase);¹¹ in the Upper Kimmeridge Clay—Portland Sand of Bucks, etc. (albite);¹² in the later Tertiary deposits of East England (albite, oligoclase);¹³ in the Dartmoor detritals (albite, oligoclase).¹⁴

Possible Sources of Derivation. Igneous rocks.

REMARKS.—The most commonly occurring member of the group in sediments seems to be Oligoclase, the more lime-bearing feldspars being easily altered. Microperthite grains have also been noted.

¹ J. J. H. Teall, "Geology of N.W. Highlands," *Mem. Geol. Surv. Scot.*, 1907, ch. xvi., p. 285.

² Author's observations.

³ G. S. Sweeting, *Proc. Geol. Assoc.*, xxxviii., 1927, p. 551.

⁴ G. S. Sweeting, *op. cit.*, p. 557.

⁵ W. F. Fleet, *Geol. Mag.*, lxviii., 1926, p. 512.

⁶ A. Heard & R. Davies, *Q.J.G.S.*, lxxx., 1924, p. 499.

⁷ A. Gilligan, *Q.J.G.S.*, lxxv., 1919, p. 262.

⁸ T. O. Bosworth, "Keuper Marls around Charnwood," Leicestershire, *Leicester Lit. & Phil. Soc.*, p. 93.

⁹ H. H. Thomas, *Q.J.G.S.*, lxvi., 1909, p. 231.

¹⁰ P. G. H. Boswell, *Geol. Mag.*, lxi., 1924, p. 258.

¹¹ J. G. A. Skerl, *Proc. Geol. Assoc.*, xxxviii., 1927, p. 385.

¹² E. Neaverson, *Proc. Geol. Assoc.*, xxxvi., 1925, p. 251.

¹³ I. S. Double, *Proc. Geol. Assoc.*, xxxv., 1924, p. 336.

¹⁴ A. Brammall, *Proc. Geol. Assoc.*, xxxix., 1928, p. 46.

General Reference.

Harold L. Alling, "The Mineralography of the Feldspars," *Journ. Geol.*, xxxi., 1923, pp. 282-305, 353-375. See also Bibliography under "Mackie" (p. 495).

PYRITE. [Fig. 60. Pl. XVI.]

Chem. Comp. FeS_2 .

System. Cubic.

Habit. Cubic, dodecahedral, "pyritohedral" and combinations of different forms. Often twinned (interpenetrant); cubic faces frequently striated.

Structure. Crystalline, massive.

Cleavage. Poor parallel to (100) and (111).

Fracture. Conchoidal.

Hardness. 6 to 6.5.

Spec. Grav. 4.967 to 5.100.

Lustre. Metallic, splendid.

Colour. Brass-yellow, sometimes tarnished.

Mag. Prop. Non-magnetic.

Elect. Prop. Good conductor.

Opt. Prop. Opaque.

Characters in Sediments. Commonly occurs in well crystallized dodecahedra or "pyritohedra," the latter often in complex interpenetration. Other forms are nodular, botryoidal; sometimes masses of minute crystals unite to produce aggregates of fantastic appearance, especially when the mineral is intimately associated with lignite, as in clays. The brass-yellow colour and lustre by reflected light are very characteristic, as is also the tarnish (a dull blackish-brown veneer) due to alteration, probably to limonite. Simple cubic grains are rare.

Occurrence. In most argillaceous rocks, especially Jurassic and Cretaceous clays in England. Prolific in many of the Cambrian, Ordovician and Silurian shales of Wales and the Welsh borderland;¹ in the Devonian and Culm Beds of the Torquay district;² in the Permian rocks of the Torquay Promontory;³ in the Northampton Ironstone;⁴ in the Fairlight Clays of Fairlight, Sussex;⁵ in the Wadhurst Clay (Wealden) generally;⁶ in the

¹ Author's observations.

² W. G. Shannon, *Proc. Geol. Assoc.*, xxxix., 1928, pp. 137-153.

³ W. G. Shannon, *Proc. Geol. Assoc.*, xxxviii., 1927, pp. 133-144.

⁴ J. G. A. Skerl, *Proc. Geol. Assoc.*, xxxviii., 1927, p. 380.

⁵ H. B. Milner, *Proc. Geol. Assoc.*, xxxvi., 1925, p. 315.

⁶ Author's observations.

Weald Clay, Atherfield Clay, Sandgate Beds (Lower Greensand), Woolwich and Reading loams, London Clay of the Croydon Regional Survey area (Surrey, etc.);¹ in the Dartmoor detritals.²

Possible Sources of Derivation. Igneous and sedimentary rocks, metalliferous veins; chiefly authigenous.

REMARKS. — Pyrite is more common in detrital sediments than its isomer marcasite (q.v.), except in certain local cases. It may be removed from residues (if necessary) by boiling with weak HNO_3 .

¹ G. M. Davies, *Proc. Croydon Nat. Hist. Soc.*, 1915-16, pp. 82-85.

² A. Brammall, *Proc. Geol. Assoc.*, xxxix., 1928, p. 35.

PYROLUSITE.

Chem. Comp. MnO_2 .

System. Doubtful (?Orthorhombic).

Habit. Probably pseudomorphous after manganite.

Structure. Normally amorphous, massive.

Cleavage. None.

Fracture. Splintery, uneven.

Hardness. 2 to 2.5.

Spec. Grav. 4.75.

Lustre. Metallic, dull.

Colour. Purplish-black.

Mag. Prop. Weakly magnetic.

Elect. Prop. Moderate conductor.

Opt. Prop. Opaque.

Characters in Sediments. Usually occurs in the form of irregular purplish or dead black grains, void of all crystalline structure. Boswell thus notes one occurrence: "It has a flat irregular and angular form, is dull black by reflected light, but sometimes shows striations or flutings characteristic of the mineral."³

Occurrence. In the Fairlight Clays (Wealden) of Sussex;¹ in the Chalk of Surrey, etc.;² in the Thanet Beds (Eocene) of the N.E. London Basin.³

Possible Sources of Derivation. Of secondary origin, derived by oxidation of manganese present in various rocks; metalliferous veins; organic.

REMARKS.—Pyrolusite occurs chiefly as an authigenous constituent of detrital sediments, also frequently as dendritic aggregates on the joint planes of sediments, and on individual pebbles. Should always be confirmed by chemical test: borax bead attains a violet-red colour in oxidising flame; fused with Na_2CO_3 yields a bluish-green mass.

¹ H. B. Milner, *Proc. Geol. Assoc.*, xxxvi., 1925, pp. 312-315.

² G. M. Davies, *Proc. Croydon Nat. Hist. Soc.*, 1915-16, p. 89.

³ P. G. H. Boswell, *Q.J.G.S.*, lxxi., 1915, p. 577.

PYRRHOTITE.

Chem. Comp. $\text{Fe}_n\text{S}_{(n+1)}$, with impurities such as Cu, Ni and Co.

System. Hexagonal.

Habit. Tabular, prismatic with pyramidal terminations.

Structure. Massive, less commonly crystalline.

Cleavage. Fair parallel to (0001), poor parallel to (11 $\bar{2}$ 0).

Fracture. Uneven.

Hardness. 3.5 to 4.5.

Spec. Grav. 4.58 to 4.64.

Lustre. Metallic.

Colour. Bronze-yellow, reddish-yellow, blackish-brown.

Mag. Prop. Strongly magnetic.

Elect. Prop. Good conductor.

Opt. Prop. Opaque.

Characters in Sediments. This species, when present in detrital sediments, is invariably irregular (ragged) in form, and exhibits a characteristic bronze lustre in reflected light. Rapidly alters to limonite, evidenced by appearance of ochreous patches noted in many examples.

Occurrence. In the Upper Lias—Lower Inferior Oolite sands of the West of England;¹ in the Arctic Bed (Late Glacial) of the Lea Valley;² in the dune sands of South Wales (derived from the Pennant Grit and Llynfi rock, Swansea Bay).³

Possible Source of Derivation. Basic igneous rocks; metalliferous veins. In some cases authigenic.

REMARKS.—Relatively uncommon in detrital sediments, but when present it is apparent from the preliminary examination of the sample. It is readily dissolved in HCl, and therefore does not appear in the cleaned "heavy" residue. Its highly magnetic properties and lustre serve to distinguish it from pyrite and chromite, with which it may possibly be confused.

¹ P. G. H. Boswell, *Geol. Mag.*, lxi., 1924, p. 258.

² G. M. Davies, *Q.J.G.S.*, lxviii., 1912, p. 247.

³ A. Stuart, *Proc. Geol. Assoc.*, xxxv., 1924, p. 323.

QUARTZ. [Fig. 61. Pl. XVII]

Chem. Comp. SiO_2 .

System. Rhombohedral.

Habit. Prismatic, with positive and negative rhombohedron terminations.

Structure. Crystalline, cryptocrystalline, massive.

Cleavage. Rare parallel to (10 $\bar{1}$ 1) and (01 $\bar{1}$ 1).

Fracture. Conchoidal.

Hardness. 7.

Spec. Grav. 2.660.

Lustre. Vitreous.

Colour. Colourless, purple, black, pink, yellow. Transparent to translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Bad conductor.

Opt. Prop. R.I. low, $\epsilon = 1.55328$, $\omega = 1.54418$. Birefringence low, $\epsilon - \omega = 0.0091$. Optically uniaxial, positive. Rarely biaxial with $2E = 12^\circ - 24^\circ$ (Winchell). Prismatic sections give straight extinction. Slow vibrations parallel to length of crystal (ϵ).

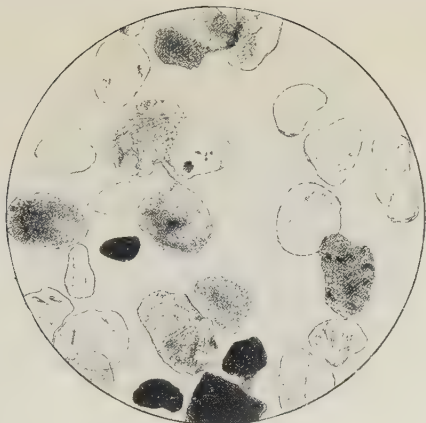
Characters in Sediments. Very variable in form and size, but usually in subangular, irregular grains unless occurring in æolian deposits, when the roundness of the grains is marked. Very beautiful, doubly terminated euhedra occur in some sediments, often showing evidence of secondary crystallization (external crystal faces in optical continuity with central nucleus). The common character of detrital quartz is that of the shapeless, slightly turbid grain with sharply defined inclusions: diagnosed by its low R.I. (almost the same as Canada balsam) and, in the majority of cases, by the "concentric ring" interference colours yielded by grains of prismatic derivation; basal grains are isotropic and normally exhibit a positive interference figure. Inclusions are either fluid or mineral; the latter may be rutile, apatite, sillimanite, tourmaline, zircon or iron-ores, the former being gaseous or liquid. Grains often exhibit undulose extinction, due to strain.

Occurrence. Ubiquitous in detrital sediments. The following examples have been selected as covering practically all variations:—in the Torridonian Sandstone of Scotland;¹ in the Malvern Quartzite (Cambrian);²

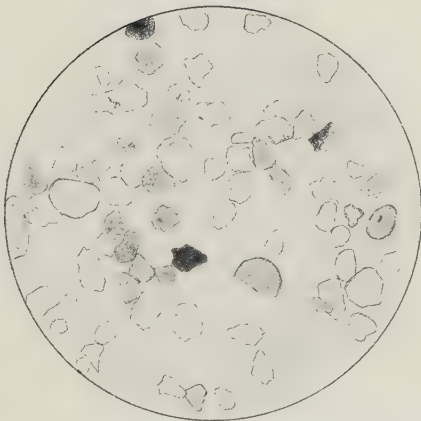
¹ J. J. H. Teall, "Geology of the N.W. Highlands," *Mem. Geol. Surv. Scot.*, 1907, ch. xvi., p. 284.

² G. S. Sweeting, *Proc. Geol. Assoc.*, xxxviii., 1927, p. 550.

A



B



C

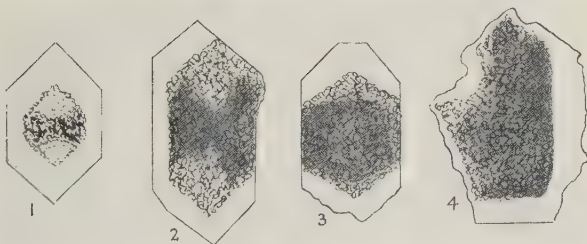


FIG. 61. QUARTZ.

A. Blown Sand, Newgale, Pembrokeshire. [x 25.] (Note degree of rounding.)

B. Tunbridge Wells Sand, Eridge, Sussex. [x 15.]

C. Euhedra, etc., extracted from Carboniferous Limestone, Halkyn, N. Wales. [x 35.]

To face page 226.

in the Old Red Sandstone of the Cardiff district;¹ in the Carboniferous Limestone of Halkyn, N. Wales;² in the Millstone Grit of Yorkshire;³ in the Keuper Marls of Charnwood, Leicestershire;⁴ in the Penrith Sandstone (Permian) of Penrith, Cumberland;⁵ in the Wealden Sands of Kent and Sussex;⁶ in the Lower Greensand, etc., of Surrey;⁷ in the later Tertiary deposits of East England;⁸ in the dune sands of South Wales;⁹ in Dartmoor detritals.¹⁰

Possible Sources of Derivation. Acid and intermediate rock types, more rarely basic. Sedimentary and crystalline metamorphic rocks. Metalliferous veins.

REMARKS.—Quartz is the most prolific constituent of detrital sediments, especially of the arenaceous and argillaceous types. Its detailed study in the "lighter" portion of the sediment is of great consequence, particularly when inclusions are present; these are, by their nature and abundance, frequently valuable indices of provenance.†

¹ A. Heard & R. Davies, *Q.J.G.S.*, lxxx., 1924, pp. 497-499.

² Author's observations (see *fig.* 61, C).

³ A. Gilligan, *Q.J.G.S.*, lxxv., 1919, pp. 259-262.

⁴ T. O. Bosworth, "Keuper Marls around Charnwood," Leicestershire, *Leicester Lit. & Phil. Soc.*, pp. 89-92.

⁵ Well-known occurrence: see Harker, "Petrology for Students," 1919, p. 206.

⁶ Author's observations, particularly the Tunbridge Wells Sand (Wealden) of Eridge, etc., Sussex.

⁷ G. M. Davies, *Proc. Croydon Nat. Hist. Soc.*, 1915-16, p. 87.

⁸ I. S. Double, *Proc. Geol. Assoc.*, xxxv., 1924, p. 335.

⁹ A. Stuart, *Proc. Geol. Assoc.*, xxxv., 1924, p. 323.

¹⁰ A. Brammall, *Proc. Geol. Assoc.*, xxxix., 1928, p. 46.

General References.

C. Raeburn & H. B. Milner, "Alluvial Prospecting," 1927, pp. 416-421 (for alluvial quartz and varieties).

P. G. H. Boswell, "British Resources of Sands and Rocks used in Glass-making," 2nd ed., 1918 (for British quartzose sands of different stratigraphical ages, size and shape of grains, mechanical analyses, etc.).

† W. Mackie, *Trans. Edinburgh Geol. Soc.*, vii., 1897, pp. 148-172. (Inclusions in quartz, etc.)

RUTILE. [Fig. 62. Pl. XVIII.]

Chem. Comp. TiO_2 .

System. Tetragonal.

Habit. Prismatic, acicular. Frequently striated parallel to principal axis, with transverse striæ parallel to (101) due to polysynthetic twinning. Sometimes twinned about (101), either geniculate or as a network (Sagenite).

Structure. Crystalline.

Cleavage. Good parallel to (110) and (100). Occasionally parallel to (111).

Fracture. Subconchoidal.

Hardness. 6 to 6.5.

Spec. Grav. 4.18 to 4.25.

Lustre. Metallic to vitreous.

Colour. Red, reddish-brown, yellow.

Mag. Prop. Non-magnetic.

Elect. Prop. Moderately good conductor.

Opt. Prop. R.I. very high, $\epsilon = 2.9029$, $\omega = 2.6158$. Birefringence high, $\epsilon - \omega = 0.2871$. Optically uniaxial, positive. Interference figure anomalous in twinned crystals, giving biaxial characters, "twinning bands crossing basal sections of the uniaxial mineral; in these bands the optic plane is $\parallel 110$ " (Winchell). Length slow. Red and brown varieties usually pleochroic, weak: reddish-brown to brown or yellow. Maximum absorption direction parallel to principal axis. Straight extinction.

Characters in Sediments. Two types of rutile are frequently met with, well-formed prismatic grains with pyramidal terminations, often slightly rounded, and anhedral fractured grains; the former are usually "foxy-red," reddish-brown or yellow in colour, the latter being more commonly of an amber tint. The degree of rounding of grains is a variable factor, often being slight compared with associated minerals. In addition, geniculate twins are found in certain sands, especially in alluvials, the two individuals making an angle of about 65° with one another. Many prismatic grains exhibit characteristic striations running obliquely to the prism-edge, due to polysynthetic twinning parallel to (101). Inclusions of iron-ore rare. Diagnosed chiefly by tetragonal (prismatic) form and cleavage, brilliant metallic to vitreous lustre, colour,



FIG. 62. RUTILE.

- 1, 6, 7. Lower Greensand, N.W. Wiltshire. [x 70.]
 2-4. Tunbridge Wells Sand, Kent. [x 60.]
 5. Geniculate twin, Tunbridge Wells Sand, Kent. [x 100.]
 8. do. Recent Sands, Ceylon. [x 70.]

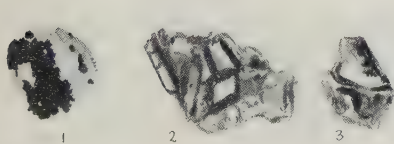


FIG. 63. SERPENTINE.

- 1-3. Shore Sand, Kynance, Cornwall.
 [x 45.]

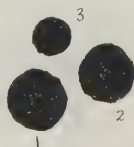


FIG. 64.

SPHERULITIC
 SIDERITE.

- 1-3. Fairlight Clay,
 Fairlight Glen,
 Hastings, Sussex.
 [x 45.]

PLATE XVIII.

high R.I. and diagonal striæ when developed. (For Sagenite, see below under Remarks).

Occurrence. Extremely common in detrital sediments from all geological horizons. The following occurrences and records cover practically all types noted:— in the Bunter Pebble Beds of the West of England;¹ in the Upper Lias—Lower Inferior Oolite sands of the West of England;² in the Northampton Ironstone;³ in the Upper Tunbridge Wells Sands (Wealden), Tunbridge Wells, Kent;⁴ in the Lower Greensand of N.W. Wilts⁵ and Cambridgeshire,⁶ etc.; in all Lower Tertiary sands of the Hampshire and London basins;⁷ in the Pliocene sands of Cornwall;⁸ in the later Tertiary deposits of East England;⁹ in the dune sands of South Wales;¹⁰ in Dartmoor detritals.¹¹

Possible Sources of Derivation. Acid igneous rocks, crystalline metamorphic rocks. Frequently derived *in situ* from the decomposition of ilmenite.

REMARKS. — Sagenite, the "lattice" form of rutile, composed of a number of individuals involved in geniculate twinning, is an infrequent occurrence in detrital sediments. When present it probably owes its preservation to a host such as biotite or chlorite from which it is released by their decomposition.

¹ H. H. Thomas, *Q.J.G.S.*, lviii., 1902, p. 622.

² P. G. H. Boswell, *Geol. Mag.*, lxi., 1924, pp. 253-254.

³ J. G. A. Skerl, *Proc. Geol. Assoc.*, xxxviii., 1927, p. 380.

⁴ H. B. Milner, *Proc. Geol. Assoc.*, xxxiv., 1923, p. 49 & pl. v.

⁵ Author's observations.

⁶ R. H. Rastall, *Geol. Mag.*, 1919, p. 219.

⁷ General observations; see particularly P. G. H. Boswell, *Q.J.G.S.*, lxxi., 1915, pp. 576, 581, & table iv. (for N.E. London basin); S. W. Wooldridge, *Proc. Geol. Assoc.*, xxxv., 1924, p. 379 (for Bagshot Beds of Essex).

⁸ H. B. Milner, *Q.J.G.S.*, lxxviii., 1922, pp. 359, 361.

⁹ I. S. Double, *Proc. Geol. Assoc.*, xxxv., 1924, p. 338.

¹⁰ A. Stuart, *Proc. Geol. Assoc.*, xxxv., 1924, p. 322.

¹¹ A. Brammall, *Proc. Geol. Assoc.*, xxxix., 1928, p. 34; also A. Brammall & H. F. Harwood, *Mineralogical Mag.*, xx., 1923, pp. 20-26.

General Reference.

C. Raeburn & H. B. Milner, "Alluvial Prospecting," 1927, pp. 422-3 (for alluvial rutile, sagenite, etc.).

SERPENTINE. [Fig. 63. Pl. XVIII.]

Chem. Comp. $H_4Mg_3Si_2O_{10}$.

System. Monoclinic or ?Orthorhombic.

Habit. Pseudomorphous.

Structure. Fibrous, lamellar, massive, "net-like."

Cleavage. Sometimes good parallel to (100).

Fracture. Subconchoidal, splintery.

Hardness. 2.5 to 4. Rarely 5.5.

Spec. Grav. 2.50 to 2.65.

Lustre. Greasy, wax-like in massive varieties, silky in fibrous varieties.

Colour. Green, blackish-green, brown, brownish-red, yellow. Colour may be considerably bleached. Translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. low (varies), $\alpha = 1.560$, $\beta = 1.570$, $\gamma = 1.571$.

Birefringence low, $\gamma - \alpha = 0.011$ (these values for the *Antigorite* variety); Rosenbusch records a mean R.I. of 1.54 and $\gamma - \alpha = 0.013$ as a maximum for one type of *Chrysotile*. R.I. of most Cornish detrital serpentine is between 1.56 and 1.65, but varies with composition.

Optically biaxial, negative, in lamellar varieties, (*e.g.*, *Antigorite*), and positive in fibrous varieties (*e.g.*, *Chrysotile*). Optic axial plane parallel to (100). $Bxa = X$ normal to (010) in lamellar types, or parallel to length of fibres in fibrous types. $X \parallel b$, $Y \parallel a$, $Z \parallel c$.

Sometimes $X \parallel c$. $2V = 20^\circ - 90^\circ$ (Levy and Lacroix); $2E = 16^\circ - 98^\circ$ (*Antigorite*), $2E = 16^\circ - 30'$ (*Chrysotile*).

Pleochroism: a faint colour-change sometimes noted in the lamellar varieties.

Characters in Sediments. Detrital serpentine is an extremely variable mineral in sediments; it is usually quite irregular in shape, of a green or greenish-brown colour, often crowded with inclusions of iron-ore, and shows characteristic "bluish-yellow-green" polarisation tints which, together with its low refractive index, serve as a diagnostic property. The original mineral, after which serpentine is pseudomorphous, is normally impossible to discern with detrital grains, though sometimes olivine is strongly suggested.

Occurrence. In the Devonian and Culm sediments of the Torquay district;¹ in the Permian rocks of the Torquay Promontory;² in the New Red Sandstone of the West of England;³ in the Sands of the Upper Lias—Lower Inferior Oolite of the West of England;⁴ in the shore-sands in proximity of the serpentine masses of the Lizard district, Cornwall;⁵ in recent deposits of Pavia, etc., northern Italy;⁶ in deposits of doubtful age (?Eocene) of Marazion, Cornwall.⁷

Possible Sources of Derivation. Ultrabasic igneous rocks. Alteration product of non-aluminous ferro-magnesian minerals such as olivine and certain amphiboles and pyroxenes.

REMARKS.—Serpentine is decomposed by hydrochloric acid, so if anticipated it must be searched for in the original washed sample; it floats in bromoform except when associated with much iron-ore.

¹ W. G. Shannon, *Proc. Geol. Assoc.*, xxxix., 1928, pp. 139, 142.

² W. G. Shannon, *Proc. Geol. Assoc.*, xxxviii., 1927, p. 134.

³ H. H. Thomas, *Q.J.G.S.*, lxx., 1909, p. 239.

⁴ P. G. H. Boswell, *Geol. Mag.*, lxi., 1924, p. 252.

⁵ Author's observations.

⁶ E. Tacconi, *Rendic. R. Ist. lomb.*, ser. 2, xxxiv., 1901, pp. 873-881.

⁷ P. G. H. Boswell, *Q.J.G.S.*, xxix., 1923, pp. 213, 226.

SIDERITE. [Fig. 64. Pl. XVIII.]

Chem. Comp. FeCO_3 .

System. Rhombohedral.

Habit. Simple rhombohedron, often with curved faces. Spherulitic.

Structure. Crystalline, massive, compact, radiating in spherulites.

Cleavage. Perfect rhombohedral, parallel to (1011).

Fracture. Uneven.

Hardness. 3.5 to 4.

Spec. Grav. 3.83 to 3.88.

Lustre. Vitreous, dull.

Colour. Shades of brown or grey. Translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Bad conductor.

Opt. Prop. R.I. high, $\omega = 1.8724$, $\epsilon = 1.6338$. Birefringence very high, $\omega - \epsilon = 0.2386$. Optically uniaxial, negative. In translucent grains, "twinkling," due to different R.I. values, noted on rotation of polariser alone. Radiating masses exhibit brush-polarisation (or black cross) effects.

Characters in Sediments. Subangular or rounded rhombohedral grains determined principally by cleavage. Also as spherulitic or slightly ellipsoidal grains of characteristic form, colour, and traces of radiate structure on fractured edges.

Occurrence. In the Devonian rocks of the Torquay district;¹ in the Upper Coal Measures of South Wales;² in the Etruria Marls and Blackband Group (Upper Coal Measures) of Staffordshire;³ in the Marlstone Ironstone (Middle Lias) of Leicestershire;⁴ in the Fairlight Clays (Wealden) of Fairlight, Sussex;⁵ in St. Ives Bay sand, Cornwall.⁶

¹ W. G. Shannon, *Proc. Geol. Assoc.*, xxxix., 1928, p. 142.

^{2, 3} E. Spencer, *Q.J.G.S.*, lxxxi., 1925, pp. 675-677.

⁴ W. A. Richardson, *Trans. Inst. Min. Eng.*, lx., 1921, pp. 337-344.

⁵ H. B. Milner, *Proc. Geol. Assoc.*, xxxvi., 1925, p. 315; also E. Spencer, *op. cit. sup.*, p. 670.

⁶ T. Crook & G. M. Davies, *Geol. Mag.*, 1909, p. 122.

Possible Sources of Derivation. Clay ironstone and allied stratified deposits, also from metalliferous veins.

REMARKS.—By no means a common mineral in detrital sediments, only occurring locally under suitable conditions.

General Reference.

E. Spencer, "On Occurrences of Spherulitic Siderite, etc., in Sediments," *op. cit.*, p. 232.

SILLIMANITE. [Fig. 65. Pl. XIX.]

Chem. Comp. $\text{Al}_2\text{O}_3 \cdot \text{SiO}_2$.

System. Orthorhombic.

Habit. Prismatic, with irregular terminations, fibrous. Sometimes striated.

Structure. Crystalline.

Cleavage. Good parallel to (010).*

Fracture. Irregular.

Hardness. 6 to 7.

Spec. Grav. 3.23 to 3.24.

Lustre. Vitreous.

Colour. Usually colourless or pale shades of brown, green, or grey. Transparent.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. high, $\alpha = 1.6603$, $\beta = 1.6612$, $\gamma = 1.6818$.

Birefringence high, $\gamma - \alpha = 0.0215$. Optically biaxial, positive. $Bxa = Z$ normal to (001), i.e., parallel to c , hence positive elongation. $Z \parallel c$, $Y \parallel b$, $X \parallel a$.* Optic axial plane parallel to (010). $2E = 42^\circ 30'$ (varies). Straight extinction parallel to the prism edge. Compensates $\perp$ to length. Occasionally pleochroic, especially if much coloured: dark to pale shade. Strong dispersion, $\rho > \nu$.

Characters in Sediments. Usually found as long slender prisms or fibres, sometimes flattened, with fractured or irregular terminations. Tendency to display traces of longitudinal "splitting." Flattened grains parallel to (001) exhibit good biaxial figure and low birefringence due to $\beta - \alpha = 0.0009$. Grains with regular striations are comparatively rare; curved forms are occasionally met with. Inclusions of spinel, biotite or glass (Winchell).

Occurrence. In the Bunter Pebble Beds of the West of England;¹ in the New Red Sandstone of the West of England;² in the Lower Greensand of Limpsfield,

¹ H. H. Thomas, *Q.J.G.S.*, lviii., 1902, p. 621.

² H. H. Thomas, *Q.J.G.S.*, lxx., 1909, p. 231.

**Note.*—Some discrepancy exists in the records of cleavage, optical directions, etc., some authorities giving perfect cleavage $\parallel$ (100), $X \parallel b$, etc. Cf. Dana, Iddings, and Larsen, Winchell, *op. cit.*

Surrey;¹ in the Lenham Beds, Sanderstead, Surrey;² in the Red Crag, Bentley, Suffolk;³ in the later Tertiary deposits (Red Crag, Norwich Crag, Chillesford Beds, Forest Bed and *Leda myalis* Bed) of East England;⁴ in deposits of doubtful age, Marazion, Cornwall;⁵ in the Dartmoor detritals.⁶ "Its occurrences in the Bunter, Upper Lias, Inferior Oolite, Callovian, Thanet Beds, Reading Beds, Claygate Beds, Bagshot Beds, Upper Headon Beds, and the Pliocene of East Anglia and Cornwall, as well as more recent deposits in Scotland, Ireland and England, are sporadic and rare."⁷

Possible Sources of Derivation. Crystalline metamorphic rocks.

REMARKS.—Sillimanite is essentially a local species. It is distinguished from topaz and andalusite by its higher birefringence and smaller axial angle, andalusite having negative, sillimanite positive elongation; from kyanite, which at first sight it often resembles, by straight extinction, high interference colours and lower R.I.

¹ G. M. Davies, *Proc. Croydon Nat. Hist. Soc.*, 1915-16, p. 91.

² F. Gossling and S. W. Wooldridge, *Proc. Geol. Assoc.*, xxxvii., 1926, p. 99.

³ Author's observations.

⁴ I. S. Double, *Proc. Geol. Assoc.*, xxxv., 1924, p. 340.

⁵ P. G. H. Boswell, *Q.J.G.S.*, lxxix., 1923, p. 226.

⁶ A. Brammall, *Proc. Geol. Assoc.*, xxxix., 1928, p. 47.

⁷ P. G. H. Boswell, "The Rarer Detrital Minerals of British Sedimentary Rocks," *Trans. Geol. Soc. Glasgow*, xviii., 1926-27, p. 140.

SPHALERITE (Zinc Blende). [Fig. 66. Pl. XIX.]

Chem. Comp. ZnS .

System. Cubic.

Habit. Tetrahedral, dodecahedral or combination of cube and dodecahedron. Frequently twinned: twin lamellæ parallel to the tetrahedron faces.

Structure. Crystalline, massive, granular.

Cleavage. Perfect parallel to (110).

Fracture. Conchoidal.

Hardness. 3.5 to 4.

Spec. Grav. 4 to 4.1.

Lustre. Adamantine, metallic to resinous.

Colour. Black, brown, yellow, sometimes light green. Opaque, sometimes translucent.

Mag. Prop. Weakly magnetic to moderately magnetic when Fe is present.

Elect. Prop. Good conductor.

Opt. Prop. R.I. high (in translucent crystals), $n = 2.37$. Isotropic.

Characters in Sediments. This mineral may either occur in quite opaque tetrahedral or dodecahedral grains, or in translucent brown granules of high refractive index and obvious isotropism. If in the opaque form, the striations parallel to the tetrahedral faces are usually developed, and are very characteristic. Its resinous lustre and indication of a perfect dodecahedral cleavage are further properties to be looked for. The translucent coloured grains are extremely difficult to differentiate from other similarly coloured detrital minerals, and chemical tests on bulk material (if possible) are desirable. Distinguished from rutile, brookite, cassiterite and titanite by the anisotropism of those species; but may be confused with brown garnet, chromite or picotite if in small grains.

Occurrence. In the Middle Lias (Cleveland Ironstone) of Yorkshire;¹ in the Fullers Earth (Aptian) of Redhill, Surrey;² in the shore sand of Lelant, Cornwall.³

Possible Sources of Derivation. From veins and irregular ore bodies in limestones; from metalliferous veins associated with galena, pyrite, copper ores, etc.

REMARKS.—In a personal communication to the author, G. M. Davies draws attention to the commonly noted association of sphalerite and Fullers Earth, not only in Aptian deposits, but also in the Jurassic Fullers Earth, e.g., Combe Hay, near Bath.

¹ J. E. Stead, *Proc. Cleveland Inst. Eng.*, 1910, pp. 75-117; also A. F. Hallimond, *Mem. Geol. Sur., Min. Res. Gt. Brit.*, xxix., "Iron Ores," 1925, p. 52.

² G. M. Davies, *Proc. and Trans. Croydon Nat. Hist. Soc.*, 1915-16, p. 86.

³ Author's observation.

SPINEL.

Chem. Comp. $\text{MgO} \cdot \text{Al}_2\text{O}_3$.

System. Cubic.

Habit. Octahedral

Structure. Crystalline.

Cleavage. Poor parallel to (111).

Fracture. Conchoidal.

Hardness. 8.

Spec. Grav. 3.52 to 3.71 (varies with composition).

Lustre. Vitreous.

Colour. Shades of red, reddish-yellow, in common Spinel; green in Ceylonite (Iron Spinel), see p. 150.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. high, 1.7135 to 1.7260, varying with composition and colour. Isotropic.

Characters in Sediments. Generally occurs as well rounded octahedral grains, much "pitted" from uneven abrasion. The conchoidal fracture, if developed, is very characteristic. Recognized by its high R.I., colour and isotropism.

Occurrence. In the dune sands of South Wales;¹ in the Dartmoor detritals;² in St. Ives Bay sand, Cornwall.³

Possible Sources of Derivation. Metamorphosed limestone, crystalline schist, dolomitic limestone.

REMARKS.—Common red spinel (excluding Ceylonite, *q.v.*) seems to be extremely rare in detrital sediments, though its resemblance to almandine garnet may have caused it to be overlooked in some instances. It differs from garnet in its lower S.G., non-magnetic properties and usual octahedral habit, but positive diagnosis by the microscope alone is certainly difficult. Appeal to R.I. test by immersion in methylene iodide is suggestive: spinel is nearly always less than, garnet, greater than that liquid (1.737). [A. Brammall].

¹ A. Stuart, *Proc. Geol. Assoc.*, xxxv., 1924, p. 321.

² A. Brammall, *Proc. Geol. Assoc.*, xxxix., 1928, p. 47.

³ T. Crook & G. M. Davies, *Geol. Mag.*, 1909, p. 122.

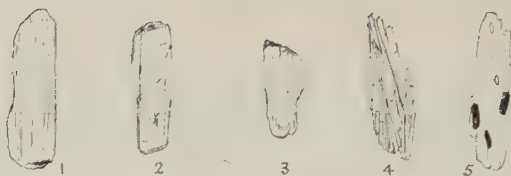


FIG. 65. SILLIMANITE.

- 1-4. Pliocene Sand, Bentley, Suffolk. [1-3, x 45] [4, x 60.]
 5. Recent Sand, Dinard, Brittany. [x 45.]



FIG. 66. SPHALERITE.

- 1-3. Middle Lias Ironstone, Cleveland, Yorkshire. [x 40.]

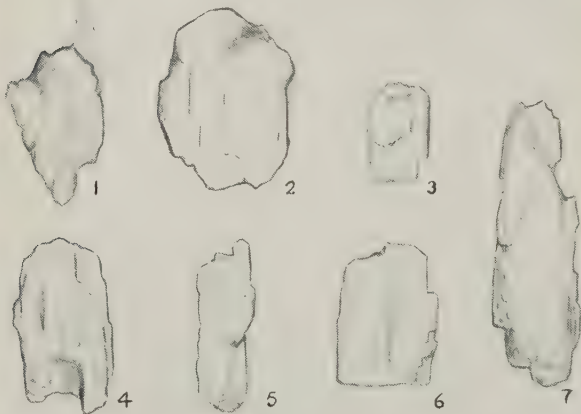


FIG. 67. SPODUMENE.

- 1-6. Recent Sand, Carrickmines, I.F.S. [x 60.]
 7. Annamoe River, I.F.S. [x 80.]
 (From Brush-drawings by F. Smithson.)

SPODUMENE. [Fig. 67. Pl. XIX.

Chem. Comp. $\text{Li}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 4\text{SiO}_2$.

System. Monoclinic.

Habit. Prismatic, often flattened parallel to (100). Also twinned about (100).

Structure. Crystalline, massive, cleavable. Lamellar parallel to (100) due to twinning. Frequently exhibits vertical striæ.

Cleavage. Perfect parallel to (110), parting parallel to (100).

Fracture. Subconchoidal, irregular.

Hardness. 6.5 to 7.

Spec. Grav. 3.13 to 3.20.

Lustre. Vitreous, pearly on (110).

Colour. Green, greenish-white, mauve, yellow, pink.

Transparent to translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Bad conductor.

Opt. Prop. R.I. high, $\alpha = 1.651$, $\beta = 1.669$, $\gamma = 1.677$.

Birefringence high, $\gamma - \alpha = 0.026$. Biaxial positive.

Optic axial plane parallel to (010). $Bxa = Z$ inclined at 26° with the c axis in the obtuse angle β . $Y = b$.

$2V = 54^\circ - 60^\circ$. Dispersion weak, $\rho < \nu$. Coloured

varieties exhibit weak pleochroism: $Z = \text{colourless}$,

$Y = \text{pink to green or mauve}$, $X = \text{purple or green}$

($X > Y > Z$). Oblique extinction, angle 26° or less.

Characters in Sediments. Occurs rarely, either as fairly perfect euhedral crystals not unlike titanite in habit, or in the form of irregular and much fractured prismatic grains of distinctive pale green, greenish-mauve or pink colour; the former approximate the variety Hiddenite, the latter (pink to lilac) Kunzite. Characterized by prismatic cleavage, often traces of parting parallel to (100), oblique extinction angle up to 26° , and sometimes by the presence of a fibrous alteration product (Cymatolite). Indeterminate inclusions observed.

Occurrence. In Pliocene-Pleistocene and Recent sands of Southern California;¹ in rocks of similar age in the Lizard area, San Joaquin Valley, California;² in sands

¹ Author's observations.

² R. D. Reed & J. P. Bailey, *Bull. Amer. Assoc. Pet. Geol.*, xi., 1927, p. 363.

and soils derived from granite, Carrickmines Golf Course, Dublin district.¹

Possible Sources of Derivation. Granite, granite pegmatite, gneiss, mica-schist.

REMARKS. — The records of this mineral occurring in detrital sediments are very scanty and it has probably been overlooked in certain cases of pyroxene-rich sediments where, from the nature of the contributing parent-rocks, it might have been expected to occur. Its optical properties are sufficiently distinctive for diagnosis, coupled with the characteristic habit, cleavage and colour. It readily yields a red flame with the blowpipe (Li_2O).

¹ F. Smithson, *Geol. Mag.*, lxx., 1928, p. 24 and fig. 2 (11, 12).

General Reference.

C. Raeburn & H. B. Milner, "Alluvial Prospecting," 1927, p. 430 (for alluvial spodumene, kunzite, etc.).

STAUROLITE [Fig. 68. Pl. XX.]

Chem. Comp. Hydrous silicate of iron, magnesium and aluminium.

System. Orthorhombic.

Habit. Prismatic; sometimes twinned about (032).

Structure. Crystalline.

Cleavage. Good parallel to (010), rarely parallel to (110).

Fracture. Subconchoidal, "hackly."

Hardness. 7 to 7.5.

Spec. Grav. 3.65 to 3.7.

Lustre. Vitreous.

Colour. Reddish-brown, brown, brownish-yellow, straw-yellow.

Mag. Prop. Weakly magnetic.

Elect. Prop. Bad conductor.

Opt. Prop. R.I. high, $\alpha = 1.736$, $\beta = 1.741$, $\gamma = 1.746$.

Birefringence low, $\gamma - \alpha = 0.010$. Optically biaxial, positive. Optic axial plane parallel to (100). $Bxa = Z \parallel c$ normal to (001). $X \parallel b$, $Y \parallel a$, $Z \parallel c$. $2V = 88^\circ$. Prismatic sections show straight extinction. Pleochroism moderate: absorption $Z > Y > X$; $Z =$ gold-yellow, $Y =$ pale yellow, $X =$ colourless. Dispersion weak, $\rho > v$.

Characters in Sediments. Well crystallized grains are comparatively rare, the usual type being irregular or somewhat platy grains determined largely by cleavage, having marked "hackly" fracture and haphazard boundaries. In a few cases, very perfect euhedra are seen, generally of a delicate lemon-yellow tint, and exhibiting the characteristic pleochroism. Grains with "concertina" boundaries (due to twinning) are sometimes met with. Intensity of pleochroism varies greatly, maximum coloration being apparent in prismatic grains orientated in an E.-W. position (parallel to short axis of polariser). Inclusions are common, especially quartz; garnet, tourmaline, rutile, biotite and carbonaceous matter have all been observed; such inclusions are usually commoner in the deeper coloured varieties. Thomas has described some well formed crystals from the New Red Sandstone of the West of England, which are tabular parallel to (010), modified by (110), and terminated by forms (101) and (001); such grains constitute a rare type in sediments generally. A still

rarer type in detrital sediments is that of the cruciform twin, the two individuals being disposed at right angles. Superficial decomposition to a form of chlorite or mica may be noted in some instances.

Occurrence. A widespread mineral in British strata; the following selection indicates the range of this mineral and exemplifies all varieties:—Upper Llandovery (Silurian), in the Halesowen Sandstone (Upper Carboniferous), in the Keele Beds (Upper Carboniferous), the Enville and Permian rocks, Bunter and Keuper Sandstones, etc., of the English Midlands;¹ in the Old Red Sandstone (Downtonian) of the West Midlands;² in the Bunter Pebble Bed of the West of England;³ in the Keuper Marls around Charnwood, Leicestershire;⁴ in the New Red Sandstone of the West of England;⁵ in the Permian Yellow Sands of Yorkshire;⁶ in the Upper Lias—Lower Inferior Oolite of the West of England;⁷ in the Northampton Ironstone;⁸ in the Portland Sand of Dorset;⁹ in the Tunbridge Wells Sand (Wealden) of Kent, etc.;¹⁰ in the Lower Greensand of Surrey;¹¹ in the Carstone of Yorkshire and Lincolnshire;¹² in the Cretaceous and Eocene of Haldon Hills, in the Oligocene of Bovey and Petrockstow, Devonshire;¹³ in the Bagshot Beds (Eocene) of Essex;¹⁴ in

¹ W. F. Fleet, *Geol. Mag.*, lxii., 1925, pp. 98-128.

² W. F. Fleet, *Geol. Mag.*, lxiii., 1926, p. 513.

³ H. H. Thomas, *Q.J.G.S.*, lviii., 1902, p. 625 & pl. xxxii., fig. 7.

⁴ T. O. Bosworth, *Q.J.G.S.*, lxviii., 1912, pp. 289-290.

⁵ H. H. Thomas, *Q.J.G.S.*, lxv., 1909, p. 234, & pl. xii., figs. 4a, 4b, 4c.

⁶ H. C. Versey, *Proc. Yorks. Geol. Soc.*, xx., 1925, p. 207.

⁷ P. G. H. Boswell, *Geol. Mag.*, lxi., 1924, p. 254.

⁸ J. G. A. Skerl, *Proc. Geol. Assoc.*, xxxviii., 1927, p. 382.

⁹ M. P. Latter, *Proc. Geol. Assoc.*, xxxvii., 1926, p. 83 *et seq.*

¹⁰ H. B. Milner, *Proc. Geol. Assoc.*, xxxiv., 1923, p. 49.

¹¹ G. M. Davies, *Proc. Croydon Nat. Hist. Soc.*, 1915-16, pp. 84-5, 92.

¹² H. C. Versey & C. Carter, *Proc. Yorks. Geol. Soc.*, xx., 1926, p. 353.

¹³ P. G. H. Boswell, *Q.J.G.S.*, lxxix., 1923, p. 226.

¹⁴ S. W. Wooldridge, *Proc. Geol. Assoc.*, xxxv., 1924, p.

the Pliocene of West Cornwall;¹ in the later Tertiary deposits of East England;² in surface deposits of S.E. Devon.³

Possible Sources of Derivation. Crystalline schists, contact metamorphic rocks.

REMARKS.—Staurolite often occurs in association with garnet, kyanite and sillimanite in metamorphic rocks, this association being common in many sediments thence derived. Very beautiful alluvial staurolite comes from the Gold Coast, Nigeria, etc. (West Africa). See General Reference below.

¹ H. B. Milner, *Q.J.G.S.*, lxxviii., 1922, p. 358.

² I. S. Double, *Proc. Geol. Assoc.*, xxxv., 1924, p. 340.

³ W. G. Shannon, *Geol. Mag.*, lxiv., 1927, p. 147.

General Reference.

C. Raeburn & H. B. Milner, "Alluvial Prospecting," 1927, pp. 432-3.

TITANITE (Sphene). [Fig. 69. Pl. XX.

Chem. Comp. $\text{CaO} \cdot \text{SiO}_2 \cdot \text{TiO}_2$.

System. Monoclinic.

Habit. Euhedral, prismatic, diamond-shaped (flattened parallel to (001)). Frequently twinned.

Structure. Crystalline.

Cleavage. Good parallel to (110), imperfect parallel to (100) and ($\bar{1}12$), rare parallel to (111). Parting parallel to (221) twin lamellæ.

Fracture. Irregular.

Hardness. 5 to 5.5.

Spec. Grav. 3.4 to 3.56.

Lustre. Vitreous.

Colour. Brown, brownish-yellow, orange, yellow-green, olive green. Translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Moderate conductor.

Opt. Prop. R.I. high, $\alpha = 1.8874$, $\beta = 1.8940$, $\gamma = 2.0093$.

Birefringence very high, $\gamma - \alpha = 0.1219$. Optically biaxial, positive. Optic axial plane parallel to (010). $Bxa = Z$ practically normal to (102). $Y = b$. Optic axial angle small but variable, $2E = 52\frac{1}{2}^\circ$. Total extinction seldom observed with white light, colour changes being from "ultra-blue" to yellows and reds. Very strong axial dispersion, $\rho > \nu$, usually well seen in the somewhat peculiar interference figure (with convergent light); this figure is generally incomplete in detrital grains, but the isogyres of the partial figure may prove of diagnostic value. In this connexion Brammell writes "the brush is broad, merely a dark grey shadow, and is reddish on the convex side, bluish on the concave side. . . ." With Wratten light-filters . . . "each colour applied in turn yields a sharper, darker brush free from marginal colour contrasts. The approximate position of the brushes for red and green respectively can usually be fixed accurately enough to verify the dispersion formula. . . ." "The direction of maximum absorption is 'slow' and rarely the direction of elongation."¹ Occasionally pleochroic in strongly coloured varieties: Z yellow or brown to X nearly colourless.

Characters in Sediments. The commonest type of detrital titanite is the irregular shaped, slightly rounded or acutely ragged grain determined principally by (110) cleavage; the diamond-shaped grains, either with

¹ See Ref. ¹⁰, p. 245.



FIG. 68. STAUROLITE.

1. Pliocene Sands, St. Erth, Cornwall. 2. Lower Greensand, N W. Wiltshire. 3-5 Alluvials W. Africa. 6. Blown Sand, Newgale, Pembrokeshire. [All x 70.]

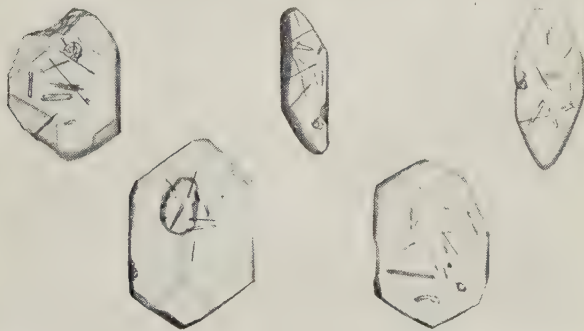


FIG. 69. TITANITE. Fullers Earth, Nutfield. [x 200.] (From Brush-drawing by E. F. Newton.)



FIG. 70. TOPAZ.

1, 2. Alluvials, Nigeria. [x 45.] 3. Lower Greensand, Poulshott Green, N.W. Wilts. [x 45.] 4. Pliocene Sand, St. Keverne, Cornwall. [x 45.]

equidimensional margins or elongated somewhat like a tetragonal bipyramid, are also observed. Perfect crystals developed in accordance with the last mentioned type, are rare: one particularly fine example has been figured by Rastall (see ref. ⁵ below). In colour titanite is usually brown to brownish-yellow, often with dusky interior; or the colour may appear bleached; more uncommon are the orange, yellow-green and olive-green types. Some crystals are observed to be traversed by a network of cracks due mainly to fracture, to a lesser degree to the combination of (110) and (100) cleavages. Diagnosed chiefly by the high R.I., colour, absence of extinction, interference figure and inclined dispersion, though there are many cases where positive diagnosis is difficult.

Possible Sources of Derivation. Granites, intermediate igneous rocks, metamorphic rocks such as gneisses, schists and altered limestones.

Occurrence. "Some of the horizons at which it is relatively plentiful are the Bunter, the Keuper, the Middle and Upper Lias, the Inferior Oolite . . . the Callovian, Kimmeridgian, Portlandian, Aptian, Albian, and the Eocene, Pliocene and Glacial deposits generally."¹ In the New Red Sandstone of the West of England;² in the Northampton Ironstone;³ in the Upper Kimmeridge Clay and Portland Sand of Bucks, etc.;⁴ in the Lower Greensand of Aspley Guise, Bedfordshire,⁵ and Great Gransden, Huntingdonshire;⁶ in the Sandgate Beds of Surrey;⁷ in the Red Crag, Chillesford Beds, Upper Crag and *Leda myalis* Bed of East Anglia (Pliocene);⁸ in the dune sands of South Wales;⁹ in the Dartmoor detritals.¹⁰

¹ P. G. H. Boswell, "The Rarer Detrital Minerals of British Sedimentary Rocks," *Trans. Geol. Soc. Glasgow*, xviii., 1926-27, pp. 136-7.

² H. H. Thomas, *Q.J.G.S.*, lxx., 1909, pp. 238-9.

³ J. G. A. Skerl, *Proc. Geol. Assoc.*, xxxviii., 1927, p. 383.

⁴ E. Neaverson, *Proc. Geol. Assoc.*, xxxvi., 1925, p. 251.

⁵ R. H. Rastall, *Geol. Mag.*, 1919, p. 267, & fig. 6.

⁶ R. H. Rastall, *op. cit.* p. 218.

⁷ G. M. Davies, *Proc. Croydon Nat. Hist. Soc.*, 1915-16, p. 93.

⁸ I. S. Double, *Proc. Geol. Assoc.*, xxxv., 1924, p. 342.

⁹ A. Stuart, *Proc. Geol. Assoc.*, xxxv., 1924, p. 324.

¹⁰ A. Brammall, *Proc. Geol. Assoc.*, xxxix., 1928, pp. 39-40.

TOPAZ.

[Fig. 70. Pl. XX.]

Chem. Comp. $(\text{AlF})_2\text{SiO}_4$.*System.* Orthorhombic.*Habit.* Prismatic, with pyramidal terminations, domes and basal plane.*Structure.* Crystalline, granular.*Cleavage.* Perfect basal parallel to (001), imperfect parallel to (201) and (021).*Fracture.* Irregular, subconchoidal.*Hardness.* 8.*Spec. Grav.* 3.532 to 3.574.*Lustre.* Vitreous, subresinous; pearly on (001).*Colour.* Colourless, yellow, blue, red, green. Transparent.*Mag. Prop.* Non-magnetic.*Elect. Prop.* Bad conductor.*Opt. Prop.* R.I. high, $\alpha = 1.6155$, $\beta = 1.6181$, $\gamma = 1.6250$.Birefringence low, $\gamma - \alpha = 0.0095$. Optically biaxial, positive. Optic axial plane parallel to (010). $Bxa = Z \parallel c$, normal to (001). $Y \parallel b$, $X \parallel a$. $2V \approx 60^\circ$ (varies).

Prismatic sections give straight extinction. Optical anomalies sometimes noted in large alluvial grains.

Dispersion, $\rho > \nu$.

Characters in Sediments. Subangular irregular grains are commonest in sediments, euhedra being rare. Basal grains are of frequent occurrence (due to dominant cleavage), and these show good interference figures. Inclusions are not uncommon, these being mostly fluid; ilmenite and hæmatite inclusions have also been observed. Detrital topaz is diagnosed chiefly by its glassy, irregular habit, high relief, often a delicate bluish tinge especially on fractured surfaces, and striking yellow and red interference colours. Many grains will be found to yield beautiful positive interference figures.

Occurrence. In the Millstone Grit of Yorkshire;¹ in the New Red Sandstone of the West of England;² in the Cretaceous, Eocene of the Haldon Hills, Devonshire;³

¹ A. Gilligan, *Q.J.G.S.*, lxxv., 1919, pp. 264, 273.

² H. H. Thomas, *Q.J.G.S.*, lxx., 1909, p. 235.

³ P. G. H. Boswell, *Q.J.G.S.*, lxxix., 1923, pp. 210, 214, 226, 227.

in the Pliocene deposits of Cornwall;¹ in the Plateau deposits and Beach deposits of S.E. Devon;² in the shore sand of St. Ives Bay, Cornwall;³ in the dune sands of South Wales;⁴ in the Dartmoor detritals.⁵

Possible Sources of Derivation. Granite, greisen and other contact metamorphic rocks.

REMARKS. — Topaz is seldom an abundant mineral in detrital sediments, and it tends to be very local. It may sometimes be easily confused with andalusite, which it resembles in certain crystallographic and physical properties; it may be differentiated from that species by its cleavage, absence of any pleochroism, optically positive character and transparency, andalusite being so commonly clouded with alteration products and carbonaceous matter. On the other hand, where topaz has altered to damourite (hydro-mica), its distinction from sericitized andalusite is a matter of considerable difficulty.

¹ H. B. Milner, *Q.J.C.S.*, lxxviii., 1922, pp. 359, 362.

² W. G. Shannon, *Geol. Mag.*, lxiv., 1927, p. 147.

³ T. Crook & G. M. Davies, *Geol. Mag.*, 1909, p. 122.

⁴ A. Stuart, *Proc. Geol. Assoc.*, xxxv., 1924, p. 325.

⁵ A. Brammall, *Proc. Geol. Assoc.*, xxxix., 1928, pp. 38-9.

General Reference.

C. Raeburn & H. B. Milner, "Alluvial Prospecting," 1927, pp. 435-6 and pl. xxviii. (for alluvial topaz).

TOURMALINE. [Fig. 71. Pl. XXI.]

Chem. Comp. Complex silicate of boron and aluminium with Fe^{II}, Mg, Mn, Ca, Na, K, Li, F and hydroxyl.

System. Rhombohedral.

Habit. Prismatic, often with vertical striations, irregular.

Structure. Crystalline, massive, compact; frequently radiating or in parallel growth.

Cleavage. Imperfect parallel to (11 $\bar{2}$ 0) (rhombohedral), and bad parallel to (10 $\bar{1}$ 1). Basal parting.

Fracture. Subconchoidal.

Hardness. 7 to 7.5.

Spec. Grav. 2.98 to 3.20.

Lustre. Vitreous, resinous.

Colour. Brown, blue, green, black, brownish-black, pink; rarely colourless.

Mag. Prop. Weakly magnetic.

Elect. Prop. Moderate conductor.

Opt. Prop. R.I. high, $\omega = 1.6424$, $\epsilon = 1.6222$. Birefringence moderate, $\omega - \epsilon = 0.202$. Optically uniaxial negative. Length fast. Occasionally grains show anomalous biaxial interference figure. Prismatic grains give straight extinction. Pleochroism varies with colour, being most intense in brown varieties: brown to yellow, dark green to mauve, blue to mauve. Maximum absorption ($\omega > \epsilon$) in prismatic grains orientated in a N.-S. position.

Characters in Sediments. A ubiquitous species, occurring principally in three forms, prismatic with varied terminations, basal or quasi-basal (usually well rounded) and irregular fractured grains. The prismatic varieties may be terminated by rhombohedra and basal parting, but are often void of terminal faces, being frequently bounded by parting or irregular fracture. Pseudo-hexagonal plates flattened parallel to (0001) and modified by (11 $\bar{2}$ 0) faces have been described, but are rare; such grains and similar basal types exhibit good uniaxial interference figure. Colour and pleochroism vary greatly, the brown and dark coloured grains normally showing the strongest pleochroism; blue tourmaline (Indicolite) is invariably weak in this respect. Parti-coloured brown and blue or brown and green

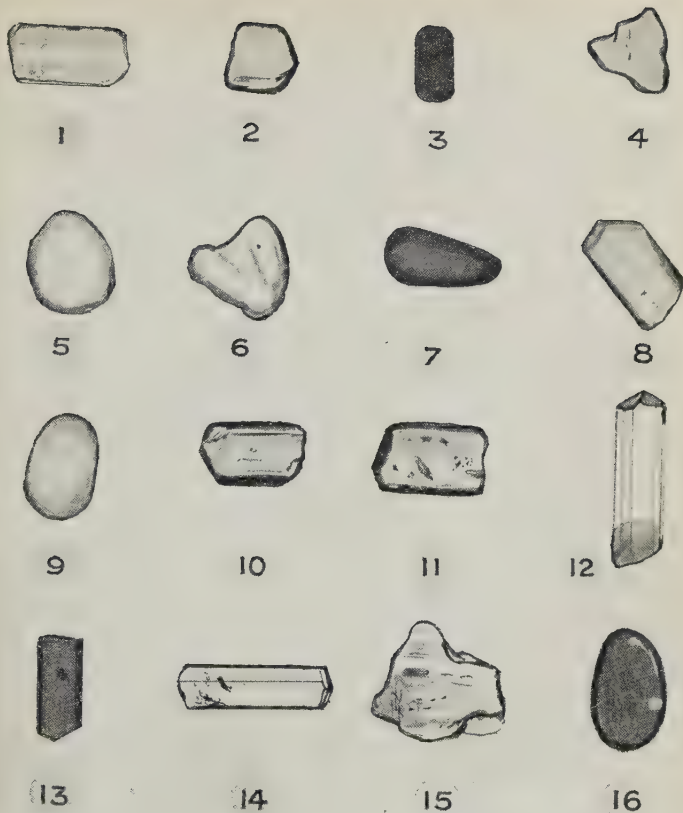


FIG 71. TOURMALINE.

- 1—3. Tunbridge Wells Sand, Tunbridge Wells, Kent. [x 70.]
 4. Ashdown Sand, Hastings, Sussex. [x 50.]
 5, 6. Glacial Sands, Withybush, Haverfordwest, Pembrokeshire. [x 40.]
 7. Blown Sand, Newgale, Pembrokeshire. [x 70.]
 8. Eocene Sand, Bromley, Kent. [x 70.]
 9. Blown Sand, Rosslare, Co. Wexford. [x 40.]
 10. Recent Sands, Brazil. [x 70.]
 11. Bagshot Sand, Hampstead, London. [x 40.]
 12. Moruga Sands (Pliocene), Trinidad. [x 70.]
 13, 14. Pliocene Sands, St. Erth, Cornwall. [x 70.]
 15, 16. Pliocene Sands, St. Erth, Cornwall. [x 40.]

To face page 248.

PLATE XXI.

mica-like flakes are frequent. Inclusions are often noted and may be cavities, zircon, rutile (both granules and needles), opaque particles, cassiterite, quartz, topaz, fluorite, feldspar, muscovite (gilbertite), anatase, brookite and water-clear sphene (A. Brammall, reference ⁵ below). Prismatic grains often show striations parallel to the principal axis. Zoning is an occasional feature (e.g., Dartmoor). The mineral is nearly always remarkably free from decomposition products, grains being normally translucent.

Occurrence. Ubiquitous in detrital sediments at most geological horizons in Great Britain. A brief selection from the prolific records of this mineral covers most of the varieties:—in the Bunter Pebble Bed of the West of England;¹ in the New Red Sandstone of the West of England;² in the Cretaceous and Tertiary outliers of the West of England;³ in the Pliocene deposits of Cornwall;⁴ in the Dartmoor detritals.⁵

Possible Sources of Derivation. Pneumatolytic rocks, acid igneous rocks, pegmatites, schists, gneisses, phyllites.

¹ H. H. Thomas, *Q.J.G.S.*, lviii., 1902, p. 624.

² H. H. Thomas, *Q.J.G.S.*, lxx., 1909, pp. 233-4.

³ P. G. H. Boswell, *Q.J.G.S.*, lxxix., 1923, pp. 208, 211, 213, 215, 218, 226-7.

⁴ H. B. Milner, *Q.J.G.S.*, lxxviii., 1922, pp. 358, 361, 363.

⁵ A. Brammall, *Proc. Geol. Assoc.*, xxxix., 1928, pp. 34-5.

General References.

A. Brammall & H. F. Harwood, "Tourmalinization in the Dartmoor Granite," *Mineralogical Mag.*, xx., 1925, pp. 319-330.

C. Raeburn & H. B. Milner, "Alluvial Prospecting," 1927, pp. 437-439 & pl. xxix. (for alluvial tourmaline and varieties).

TREMOLITE. [Fig. 72. Pl. XXII.]

Chem. Comp. $\text{CaMg}_3(\text{SiO}_3)_4$.

System. Monoclinic.

Habit. Prismatic, euhedral or irregular.

Structure. Crystalline, fibrous.

Cleavage. Well developed parallel to (110), more rarely parallel to (100) and (010).

Fracture. Subconchoidal, uneven, developed at right angles to prismatic cleavage.

Hardness. 5 to 6.

Spec. Grav. 2.930 to 3.027.

Lustre. Vitreous; pearly on cleavage flakes.

Colour. Colourless, white, grey, occasionally pink or mauve (manganese) or pale green (ferrous iron).

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. moderately high, $\alpha = 1.6065$, $\beta = 1.6233$, $\gamma = 1.6340$. Birefringence high, $\gamma - \alpha = 0.0275$. Optically biaxial, negative. Length slow. $Y \parallel b$, $Z \wedge c = 17^\circ \pm$. Optic axial plane parallel to (010). Bxo inclined at low angle to c axis: extinction angle varies from 15° to 17° . $2V = 81^\circ 22'$. Slight dispersion of the bisectrices in the plane (010). Practically non-pleochroic in colourless varieties, but perceptibly pleochroic if mauve or green.

Characters in Sediments. Diagnosis of detrital tremolite rests chiefly on its "hornblende" character *minus* the colour of that mineral, on refractive index, extinction angle and birefringence; it frequently exhibits the same sort of "ragged ends" typical of hornblende. Grey or white prismatic grains are the commonest; inclusions are indeterminate or absent. Superficial alteration to *Steatite* (noted with high power objective as minute powdery flakes or scales) is not uncommon. Fibrous varieties (*Asbestos*) not recorded from detrital sediments.

Occurrence. In sands of Chipstead, Surrey (?Pliocene);¹ in later Tertiary deposits, East England;² in recent sands of S.W. Pembrokehire and S. Cornwall;³ in re-

¹ G. M. Davies, *Proc. and Trans. Croydon Nat. Hist. Soc.*, 1915-16, pp. 77, 91.

² I. S. Double, *Proc. Geol. Assoc.*, xxxv., 1924, p. 335.

³ Author's observations.



FIG. 72. TREMOLITE.

1. Glacial Sand, Menai Straits (Anglesea). [x 60.]
 2, 3. do. Haverfordwest, Pembrokeshire. [x 40.]

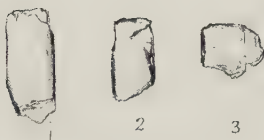


FIG. 73. ZOISITE.

- 1-3. Miocene Sand, Santa Fe Springs, Calif., U.S.A. [x 45.]

cent deposits of Pavia, etc., northern Italy;¹ in Pleistocene-Recent deposits of the Lazard area, San Joaquin Valley, California;² in Glacial Sands of the Menai Straits (Anglesey), of Haverfordwest, Pembrokeshire;³ in Glacial deposits of Kimpton, Hertfordshire.⁴

Possible Sources of Derivation. Metamorphic rocks, crystalline schists. Metamorphosed magnesian limestone. From alteration of minerals in gabbros and peridotites; from the disintegration of serpentine.

REMARKS.—Tremolite is at first likely to be confused with diopside, but is soon distinguished from that mineral by its lower extinction angle, lower refractive index and (usually) lower interference tint; also by the general absence of inclusions frequently noted in diopside.

¹ E. Tacconi, *Rendic. R. Ist. lomb.*, ser. 2, vol. xxxiv., 1901, pp. 873-881.

² R. D. Reed & J. P. Bailey, *Bull. Amer. Assoc. Pet. Geol.*, xi., 1927, p. 363.

³ Observations of G. M. Part and the author.

⁴ Observation of G. C. Flower.

VESUVIANITE (Idocrase).

Chem. Comp. $\text{Ca}_6[\text{Al}(\text{OH}, \text{F})]\text{Al}_2(\text{SiO}_4)_5$.

System. Tetragonal: holosymmetric.

Habit. Prismatic, pyramidal, the latter sometimes being a combination of prism (100) with (111) and (311); (110) often developed.

Structure. Crystalline, columnar or massive.

Cleavage. Indistinct parallel to (110), poor parallel to (100) and (001).

Fracture. Conchoidal.

Hardness. 6.5.

Spec. Grav. 3.35 to 3.45.

Lustre. Vitreous.

Colour. Brown, red, green, pale blue or yellow (rare).
Translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Poor conductor.

Opt. Prop. R.I. very high, $\omega = 1.705-1.732$, $\epsilon = 1.701-1.726$. Birefringence low, $\omega - \epsilon = 0.001-0.006$. Optically uniaxial, negative. Rarely biaxial, with variable optic axial angle: $2E = 30^\circ$ to 60° . Straight extinction. Elongation fast. Pleochroism varies, $\omega > \epsilon$: in green varieties, yellow-green to colourless; in brown varieties, yellow-brown to brownish-grey; in blue varieties, dark blue to colourless; in red varieties, red to colourless or grey.

Characters in Sediments. More detrital vesuvianite is required for study before the average characteristics of this mineral in sediments can be definitely stated. Thus far observations indicate a tendency for the grains to be prismatic, brown or greenish-brown in colour, weakly pleochroic, but in all cases typified by strong relief and weak birefringence. Other optical properties vary, both uniaxial positive and negative forms, together with biaxial crystals, being observed. [N.B.—The positive form may be the variety *Viluite*.] The uneven distribution of the colouring matter has been noted in one or two instances, also colour-zoning.

Occurrence. Possibly in the dune sands of South Wales;¹ in superficial deposits derived from the Bodmin Granite, North Cornwall;² in Pleistocene-Recent deposits of the Lazard area, San Joaquin Valley, California.³

Possible Sources of Derivation. Thermally metamorphosed limestone (in association with epidote, garnet, diopside, etc.); crystalline schist; pegmatite; gneiss.

¹ A. Stuart, *Proc. Geol. Assoc.*, xxxv., 1924, p. 322.

² Author's observations.

³ R. D. Reed & J. P. Bailey, *Bull. Amer. Assoc. Pet. Geol.*, xi., 1927, p. 363.

XENOTIME.

Chem. Comp. YPO₄.

System. Tetragonal.

Habit. Euhedral, prismatic.

Structure. Crystalline.

Cleavage. Perfect parallel to (110).

Fracture. Uneven, irregular.

Hardness. 4 to 5.

Spec. Grav. 4.45 to 4.56.

Lustre. Vitreous.

Colour. Shades of brown, brownish-red, yellow. Translucent.

Mag. Prop. Moderately magnetic.

Elect. Prop. Bad conductor.

Opt. Prop. R.I. high, $\epsilon = 1.816$, $\omega = 1.721$. Birefringence high, $\epsilon - \omega = 0.095$. Optically uniaxial, positive. Length slow. Compensates $\perp$ to length. Straight extinction. Pleochroism weak: pale yellow to brownish-yellow or yellow slightly tinged with green.

Characters in Sediments. Usually occurs as pale yellow, orange or pink, beautifully formed euhedra, doubly terminated tetragonal prisms; alternatively as rounded prismatic grains or as subangular rectangular flakes, in all cases exhibiting very high relief. The strong resemblance morphologically and optically to coloured zircon is invariable, and renders positive diagnosis of xenotime in detrital sediments a matter of great difficulty. The larger alluvial grains from recorded foreign localities afford the most promising material for study; these sometimes show patchy decomposition products recalling the cerium oxide films developed superficially on monazite.

Occurrence. In the Millstone Grit of Yorkshire;¹ in the Bunter Pebble Bed of the West of England;² in the Lower Greensand of Great Gransden, Huntingdonshire, and of Aspley Guise, Bedfordshire;³ in the Pliocene Sands of St. Agnes and St. Erth, Cornwall.⁴

(N.B.—In each of the above cases, the mineral is only recorded as a possible alternative to certain abnormal types of zircon).

¹ A. Gilligan, *Q.J.G.S.*, lxxv., 1919, p. 267.

² H. H. Thomas, *Q.J.G.S.*, lviii., 1902, p. 623.

³ R. H. Rastall, *Geol. Mag.*, 1919, pp. 218, 268.

⁴ H. B. Milner, *Q.J.G.S.*, lxxviii., 1922, pp. 357, 360.

Possible Sources of Derivation. Granites, pegmatites, intermediate rocks; less commonly gneiss.

REMARKS.—Xenotime is an exceedingly difficult mineral to differentiate from coloured zircon in detrital sediments by ordinary microscopical methods; recourse to the spectroscope should aid its positive determination, though even this is not infallible. During the last few years there has been an increasing tendency on the part of British petrographers to give coloured zircon priority of record rather than indicate a doubtful occurrence of xenotime, and short of definite chemical and spectroscopic proof of this species, this policy would seem to be more in keeping with the observed facts. The extreme rarity of the mineral, or of the equivalent coloured zircon for that matter, makes research into its detrital occurrences a difficult task. The principal differences from zircon consist in its weak magnetic properties, less tendency to exhibit inclusions, normal absence of zoning, lower R.I., and softer nature: the latter may to some extent account for its rarity.

General References.

O. A. Derby, *Mineralogical Mag.*, xi., 1897, p. 308.

In connexion with the possibility of occurrence and methods of diagnosing xenotime, see A. Brammall & H. F. Harwood, *Mineralogical Mag.*, xx., 1923, pp. 29-30. On methods of isolating and confirming xenotime in sediments, see J. Van der Lingen & A. R. E. Walker, *Trans. Geol. Soc. S. Africa*, xxviii., 1925, pp. 69-72.

ZIRCON. [Fig. 74. Pl. XXIII.]

Chem. Comp. $\text{ZrO}_2 \cdot \text{SiO}_2$.

System. Tetragonal.

Habit. Euhedral; prismatic; bipyramidal. Prisms usually elongated in the direction of the principal axis. Twinning rare.

Structure. Crystalline.

Cleavage. Imperfect parallel to (110), poor parallel to (111).

Fracture. Conchoidal.

Hardness. 7.5.

Spec. Grav. 4.2 to 4.86.

Lustre. Adamantine, vitreous.

Colour. Colourless, yellow, brown, pink, mauve, purple, rarely green.

Mag. Prop. Non-magnetic.

Elect. Prop. Bad conductor.

Opt. Prop. R.I. high, $\epsilon = 1.9682$, $\omega = 1.9239$. Birefringence high, $\epsilon - \omega = 0.0443$. Optically uniaxial, positive. Length slow. Occasionally abnormal biaxial crystals are met with. Straight extinction. Pleochroic in strongly coloured varieties.

Characters in Sediments. A common species, varying considerably in form. The prevalent type of grain is colourless, prismatic (100) or (110) or both, with pyramidal terminations (111) (331), etc. Basal grains (flattened parallel to (001)) are very scarce. Fractured grains are common, but sharply angular fragments are rare, zircon nearly always exhibiting a certain degree of rounding. Zoning is often observed and has been fully discussed by Brammall (reference below). The presence of inclusions, sometimes arranged parallel to the length of the crystal, at other times irregularly distributed, is a common feature. Inclusions may be fluid, glassy, negative crystals, or consist of minerals such as apatite and possibly xenotime. Inclusions within inclusions have also been observed. Brammall records gas-filled cavities, opaque dust in the form of stringers, clots and cloud-like suspensions, also minute zircons, monazite, hæmatite, quartz, apatite, and rarely rutile and biotite, from the Dartmoor detritals (*op. cit.*). Occasionally the grains have a dusky appearance, due

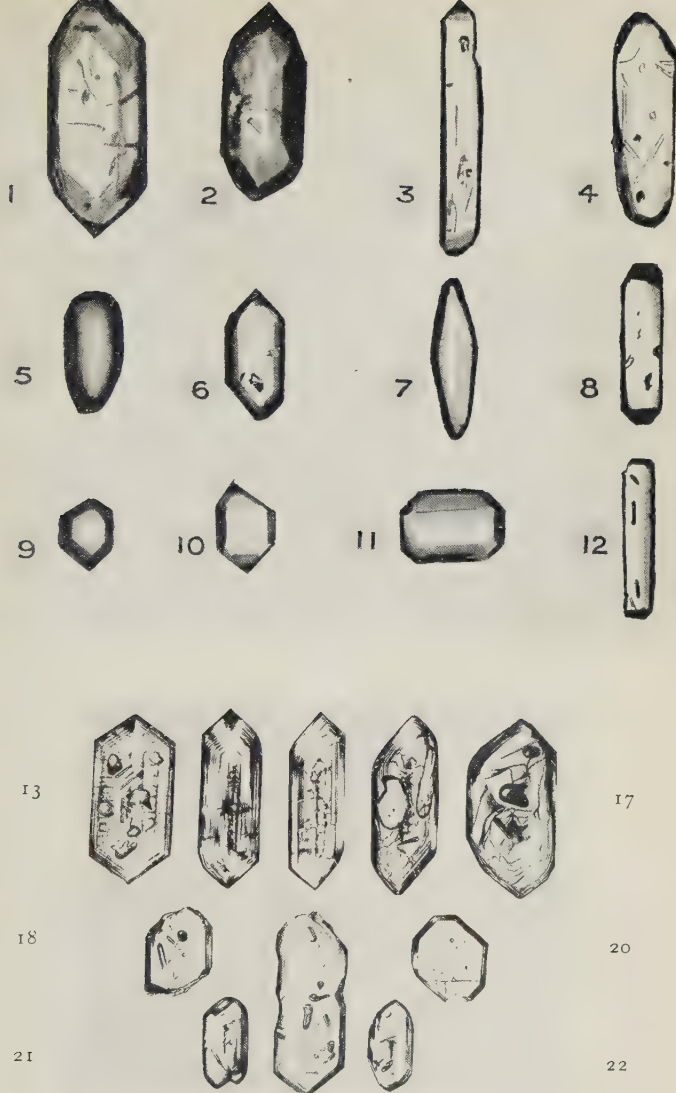


FIG 74. ZIRCON.

1, 2. Alluvials, W. Africa. 3. Bagshot Sand, Hampstead Heath, London. 4, 5. Lower Greensand, N.W. Wiltshire. 6. Wealden Sand, Shotover Hill, Oxford. 7, 8, 12. Tunbridge Wells Sand, Kent. 9-11. Ashdown Sand, Hastings, Sussex. (All $\times 100$.) 13-22. Typical Crystals and Fragments of Dartmoor Zircon; grade-size: 0.1-4 mm. (From Brush-drawings by A. Brammall.)

to the crowding of inclusions, *not* to decomposition products. Large grains with abnormal optical properties (biaxial interference figures, low birefringence, pleochroism and absence of inclusions) seem to be very local. Diagnosed essentially by its crystal form, high R.I., colour, inclusions, and zoning (when developed).

Occurrence. Ubiquitous in detrital sediments. See General References below.

Possible Sources of Derivation. Acid and intermediate igneous rocks; less commonly crystalline schists and limestones.

REMARKS. — Zircon is one of the most fascinating minerals occurring in detrital sediments, on account of its widespread occurrence throughout the geological record, and for its great variation in form, colour and intimate properties. To appreciate fully its significance in any given sediment, the most careful investigation of each variety present is essential, especially if any correlation or differentiation of the sediments involved is contemplated. Point is given to these remarks by the researches of A. Brammall and H. F. Harwood on the Dartmoor zircons, to which references, and also to other detailed accounts of this species, are given below. Confusion with xenotime is dealt with under the heading of that mineral, p. 255.

General References.

- H. H. Thomas, *Q.J.G.S.*, lviii., 1902, p. 623 & pl. xxxi., *figs.* 1-9.
A. Brammall & H. F. Harwood, *Mineralogical Mag.*, xx., 1923, pp. 27-31.
A. Brammall, *Proc. Geol. Assoc.*, xxxix., 1928, pp. 28-9, pl. ii.
W. Mackie, *Trans. Edinburgh Geol. Soc.*, xi., 1923, pp. 200-213 (purple zircon).
P. G. H. Boswell, *Mineralogical Mag.*, xxi., 1927, pp. 310-317 (distribution of purple zircon in British sediments—with many references).
C. Raeburn & H. B. Milner, "Alluvial Prospecting," 1927, pp. 444-6 & pl. xxxi. (for alluvial zircon).
K. V. Chrustchoff, "Beitrag zur Kenntnis der Zirkone in Gesteinen." *Tschermaks Min. Petr. Mitt.* vii., 1886, pp. 862-877; also *Mem. Acad. Imp. Sci. St. Petersb.*, xliii., 1894.
Zerndt, J.—See refs., p. 502.

ZOISITE. [Fig. 73. Pl. XXII.]

Chem. Comp. $\text{Ca}_2\text{Al}_2(\text{AlOH})(\text{SiO}_4)_3$.

System. Orthorhombic.

Habit. Prismatic, euhedral or irregular. Frequently striated parallel to the *c* axis.

Structure. Crystalline.

Cleavage. Perfect parallel to (010); occasionally noted parallel to (100).

Fracture. Subconchoidal, irregular.

Hardness. 6 to 6.5.

Spec. Grav. 3.25 to 3.37.

Lustre. Vitreous.

Colour. White, grey, yellowish-brown, pale green; pink or rose-red in the variety Thulite (due to Mn).

Mag. Prop. Non-magnetic.

Elect. Prop. Poor conductor.

Opt. Prop. R.I. high (varies); $\alpha = 1.696$ to 1.7002 , $\beta = 1.696$ to 1.7025 , $\gamma = 1.7020$ to 1.7058 . Birefringence low, $\gamma - \alpha = 0.0050$ to 0.0088 . In small grains (parallel to (100)) the interference tint is deep indigo-blue, almost "ultra-blue," when the optic axial angle is small. Optically biaxial, positive. $Bxa = Z$ normal to (100). $X \parallel c$, $Y \parallel b$, $Z \parallel a$, or $X \parallel b$, $Y \parallel c$, $Z \parallel a$. Straight extinction. Optic axial plane usually parallel to (010), but is not always in the same position: sometimes noted parallel to (001) [Iddings]. $2V$ varies from 0° to 60° , being largest when the optic axial plane is parallel to (001). Strong dispersion, $\rho < \nu$ or $\rho > \nu$. Pleochroism seen in large crystals: bluish-green to yellow; in Thulite it is pink to deep rose or yellow (Lacroix).

Characters in Sediments. Occurs as almost colourless grains generally determined by (010), hence prismatic habit is common. The high refractive index and low birefringence, especially the deep blue colour, are characteristic, while inclusions of amphibole microlites in the form of thin, lath-shaped, green wisps, are also a feature of this species. The mineral gives straight extinction, and is practically non-pleochroic in colourless grains; a delicate pink shade with tendency to a deeper red, denotes the variety Thulite which has perceptible pleochroism, but not as strong as that of andalusite (when developed in the latter mineral), with which there is a possibility of confusion. Andalusite has a

lower refractive index and higher birefringence than Thulite, and, of course, the latter species is far less common (see below).

Occurrence. In the Portland Sands of South Wilts. and Dorset;¹ both zoisite and thulite (?) in the dune sands of South Wales;² in various foreign sediments rich in epidote minerals, *e.g.*, Miocene sands of Los Angeles basin, California, U.S.A.³

Possible Sources of Derivation. Crystalline schists, metamorphosed basic igneous rocks; possibly from *Saussurite*, an alteration product of lime-soda felspar.

REMARKS.—Zoisite is probably a far commoner detrital mineral than generally anticipated, and owing to its similarity (if colourless) to other orthorhombic minerals, is likely to be misnamed or overlooked. The variety Thulite is more uncommon, though it may appear in recent sands in which the epidote species are strongly in evidence. Closely allied to zoisite is the monoclinic mineral *Clinozoisite*, whose presence in detrital sediments is by no means improbable; in fact, as an alternative to zoisite, it has already been recorded in one instance.⁴

CLINOZOISITE contains little iron, but otherwise is similar in composition to epidote. It exhibits the following chief properties: R.I. high, $\alpha = 1.7176$, $\beta = 1.7195$, $\gamma = 1.7232$. Birefringence low, $\gamma - \alpha = 0.0056$. Optically biaxial, positive, sometimes negative. Optic axial plane parallel to (010), perpendicular to basal cleavage (001). Bxo inclined 2° to 3° to c axis. Bxa almost normal to (100). Z inclined at 32° to a . $Y = b$. $2V = 90^\circ$ to 98° . Dispersion strong, $\rho < \nu$. In colour the mineral is grey, white or commonly colourless. It differs from zoisite in its monoclinic symmetry, oblique extinction (varying angle), much higher refractive index and often in the absence of the blue interference colour characteristic of that species, though some clinozoisite grains show this property.

¹ E. Neaverson, *Proc. Geol. Assoc.*, xxxvi., 1925, p. 251.

² A. Stuart, *Proc. Geol. Assoc.*, xxxv., 1924, p. 325.

³ Author's observations.

⁴ A. Stuart, *op. cit.*, p. 321.

SEDIMENTARY ROCK MINERALS OF SPORADIC AND LOCAL OCCURRENCE.

(Excluding those recorded *only* from Alluvial deposits.)

ÆGIRINE. (Acmite.) Variety of monoclinic pyroxene, $\text{NaFe}(\text{SiO}_3)_2$. Described from the dune sands of South Wales in which it occurs as narrow green prisms with cleavage parallel to length. Pleochroic, X=grass-green, Z=yellow. Maximum extinction angle $Z/c=70^\circ$. Medium birefringence. (A. Stuart, *Proc. Geol. Assoc.*, xxxv., 1924, p. 323.) Also recorded by W. Pawlica from the Triassic iron-ores of Galicia (*Bull. Serv. geol. Pologne*, Warsaw, vol. i., 1920, pp. 1-48).

ÆNIGMATITE. Triclinic amphibole, $\text{Na}_4\text{Fe}_9\text{AlFe}(\text{Si,Ti})_{12}\text{O}_{38}$. [Iddings.] Described from the dune sands of South Wales. Reddish-brown colour. Good prismatic cleavage; length of prism fast; intense pleochroism: X=red-brown, Z=nearly black. High R.I. (about the same as barkevicite usually), low double refraction. Extinguishes at 5° from traces of prismatic cleavage. Possibly referable to Rhönite. (A. Stuart, *Proc. Geol. Assoc.*, xxxv., 1924, p. 325.)

AGATE. Cryptocrystalline variety of silica — a variegated chalcedony. Recorded by P. G. H. Boswell, *Proc. Liverpool Geol. Soc.*, xiii., 1923, p. 268.

BASALTINE. (Basaltic Hornblende.) A type of brown hornblende found in many basaltic rocks. Recorded by R. D. Reed & J. P. Bailey from the Pleistocene-Recent deposits of the Lazard area, San Joaquin Valley, California (*Bull. Amer. Assoc. Pet. Geol.*, xi., 1927, p. 363). Also by L. Maddalena, from Eocene sandstones, etc., of West Central Italy (*C.R. Intern. Geol. Congr.*, XIIIth Session, 1922, iii., pp. 1309-1315, 1926).

BENITOITE. A rare rhombohedral mineral, $\text{BaTiSi}_3\text{O}_{10}$, described from the San Benito region, California. Recorded by R. D. Reed & J. P. Bailey from the Pleistocene-Recent deposits, Lazard area, San Joaquin Valley, California (*Bull. Amer. Assoc. Pet. Geol.*, xi., 1927, p. 363). Characterized by its deep sapphire blue colour and strong blue to colourless pleochroism. R.I. 1.77, S.G. 3.6, H. 6.2-6.5. See also C. Raeburn & H. B. Milner, *Alluvial Prospecting*, 1927, p. 447.

COLLOPHANE. (Collophanite.) Hydrous phosphate, $\text{Ca}_3\text{P}_2\text{O}_8 \cdot \text{H}_2\text{O}$. Occurs detrital in coastal deposits at Charleston, South Carolina; at Savannah, Georgia; at

Brunswick, Georgia; at Jacksonville, Florida; especially the beach deposits of the Gulf coast of Florida. Also in Quaternary and Pliocene deposits within Florida. Probably derived from phosphatic nodules, bones, etc., in a soft impure limestone of Miocene age occurring in Florida. (Communication from J. H. C. Martens of the Florida State Geological Survey to the author). See also Ch. VII, pp. 342, 350.

CROSSITE. An amphibole very similar to riebeckite occurring in lath-shaped crystals; blue in colour and with strong pleochroism. Described from the Coast Ranges of California and recorded in the Pleistocene-Recent deposits of the Lazard area, Son Joaquin Valley, California, by R. D. Reed and J. P. Bailey, *Bull. Amer. Assoc. Pet. Geol.*, xi., 1927, p. 363.

DELESSITE. Variety of chlorite usually found as an amygdaloidal filling in basalts. Recorded by P. G. H. Boswell, *Proc. Liverpool Geol. Soc.*, xiii., 1923, p. 268.

DIASPORE. Orthorhombic, hydrous oxide, $\text{Al}_2\text{O}_3 \cdot \text{H}_2\text{O}$. Prismatic, usually flattened parallel (010), also direction of perfect cleavage. S.G. 3.3-3.5. White to grey in colour. R.I. = 1.72. Pleochroic. Optically positive. Recorded by P. G. H. Boswell, *Proc. Liverpool Geol. Soc.*, xiii., 1923, p. 268.

FUCHSITE. Chromium mica. "Minute grains . . . displaying more or less rounded outline, colourless at the thinner edges but developing a bluish-green colour towards the thicker centre." Highly perfect basal cleavage. R.I. not high. Optic axial angle large; negative. Inclusions of rutile. Described by A. Stuart, from the dune sands of South Wales. Doubtful identification.* (*Proc. Geol. Assoc.*, xxxv., 1924, p. 324 and fig. 27, p. 330).

GIBBSITE. (Hydrargillite.) Monoclinic, $\text{Al}(\text{OH})_3$. Tabular crystals with pseudo-hexagonal appearance flattened parallel (001), also direction of perfect cleavage. White to grey in colour. S.G. 2.3-2.4. R.I. 1.54-1.56. Authigenic occurrence only. Doubtful identification. Recorded by P. G. H. Boswell, *Proc. Liverpool Geol. Soc.*, xiii., 1923, 1923, p. 268.

* Throughout this section "doubtful identification" implies that the author quoted has added a (?) to the particular record in question.

JASPER. Impure, opaque quartz, red, yellow, green, etc. Described from the Torridonian conglomerates *inter alia* by J. J. H. Teall. (Geology of N.W. Highlands, *Mem. Geol. Surv. Scot.*, 1907, p. 280).

LAWSONITE. Orthorhombic, $H_2CaAl_2Si_2O_{10}$. Prismatic, pale blue crystals, S.G. 3.09. R.I. 1.67. Optically positive. Described from the Tiburn Peninsula, Marin Co., California, and elsewhere, and recorded from the Pleistocene-Recent deposits of the Lazard area, San Joaquin Valley, California, by R. D. Reed & J. P. Bailey (*Bull. Amer. Assoc. Pet. Geol.* xi., 1927, p. 363).

MAGNESITE. Rhombohedral, $MgCO_3$. Properties similar to other rhombohedral carbonates, *e.g.*, calcite (*q.v.*). S.G. 3.0-3.12. R.I. $\omega=1.717$, $\epsilon=1.515$. Characteristic "twinkling" with polariser. Optically negative. Usually colourless to yellowish-white. Authigenic occurrence only. Recorded by P. G. H. Boswell, *Proc. Liverpool Geol. Soc.*, xiii., 1923, p. 267.

MELANITE. The black, dull or lustrous variety of andradite garnet. In surface deposits derived from disintegration of melanite syenites of the Assynt district, N.B. (See J. J. H. Teall, Geology of the N.W. Highlands, *Mem. Geol. Surv. Scot.*, 1907, p. 442). Recorded by P. G. H. Boswell, *Proc. Liverpool Geol. Soc.*, xiii., 1923, p. 267.

OPAL AND HYALITE. Amorphous forms of silica, opal being the white or highly coloured form, hyalite ("Mullers Glass") the glass-clear form. S.G. 1.9-2.3. R.I. 1.44-1.45. In globular grains. Recorded by P. G. H. Boswell, *Proc. Liverpool Geol. Soc.*, xiii., 1923, p. 268.

ORTHITE. (Allanite.) One of the epidote group containing rare-earth elements. Monoclinic. Either tabular or elongated prisms. Brown or black in colour. S.G. 3.0-4.2. R.I. 1.682. Oblique extinction up to 32° . Strong pleochroism, brownish-yellow to greenish-brown. Optically negative. Described from two borings in the sands, etc., of the plain of Lombardy, by I. Chelussi, *Boll. Soc. geol. ital.*, xliii., 1924, pp. 161-169.

PIEDMONTITE. Manganese epidote. S.G. 3.404. In reddish-brown or reddish-black prismatic crystals. R.I. 1.73. Low extinction angle, 3° - 6° . Optic axial plane parallel (010), positive. Strongly pleochroic. Recorded by R. D. Reed & J. P. Bailey from the Pleistocene-Recent deposits, Lazard area, San Joaquin Valley, California (*Bull. Amer. Assoc. Pet. Geol.*, xi., 1927, p. 363).

PHOSPHORITE. The amorphous, fibrous, or concretionary form of apatite. Recorded by P. G. H. Boswell, *Proc. Liverpool Geol. Soc.*, xiii., 1923, p. 268.

PSILOMELANE. A hydrous manganese oxide, generally very impure. Massive and botryoidal. In iron-black to steel-grey grains. S.G. 3.7-4.7. Recorded by P. G. H. Boswell, *Proc. Liverpool Geol. Soc.*, xiii., 1923, p. 268.

PYROPHYLLITE. One of the kaolinite group, ? monoclinic. Perfect basal cleavage. S.G. 2.8-2.9. R.I. 1.58. Cleavage flakes yield negative interference figure, very large axial angle. Colour white or green. Authigenic occurrence only. Doubtful identification. Recorded by P. G. H. Boswell, *Proc. Liverpool Geol. Soc.*, xiii., 1923, p. 268.

STRONTIANITE. Orthorhombic, SrCO_3 . Acicular crystals resembling aragonite, chiefly prismatic (110), also the direction of perfect cleavage. S.G. 3.680-3.714. White, pale green or yellow. R.I. $\alpha=2.520$, $\beta=1.667$, $\gamma=1.667$. Optically negative. "Twinkling" shown. Authigenic occurrence only. Associated with limestone at Barstow, California, and described by A. Knopf, *U.S.G.S.*, Bull. 660, 1918, pp. 257-270.

SULPHUR. Authigenic occurrence only. Recorded by P. G. H. Boswell, *Proc. Liverpool Geol. Soc.*, xiii., 1923, p. 268.

WOLFRAMITE. Monoclinic, $(\text{Fe}, \text{Mn})\text{WO}_4$. In tabular (100) crystals, dark grey in colour. Doubtfully identified in the dune sands of South Wales by A. Stuart, who describes the "irregular black metallic looking grains found with ilmenite and chromite in moderately magnetic crops. Small fragments of the powder are reddish-brown and anisotropic in very thin pieces which appear to be cleavage fragments. Very rare." It is doubtful whether this mineral could survive beyond recent deposits accumulated in proximity to its source of origin, unless protected by a host such as quartz; see C. Raeburn & H. B. Milner, *Alluvial Prospecting*, 1927, p. 114. (A. Stuart, *Proc. Geol. Assoc.*, xxxv., 1924, p. 324).

WOLLASTONITE. Monoclinic, CaSiO_3 . Tabular or short prisms with perfect cleavage parallel (100). S.G. 2.8-2.9. White to grey in colour. R.I. 1.63. Oblique extinction angle up to 32° . Optically negative. Recorded by P. G. H. Boswell, *Proc. Liverpool Geol. Soc.*, xiii., 1923, p. 268.

CHAPTER VII.

THE PETROGRAPHY OF CONSOLIDATED SEDIMENTS.*

Preliminary to any survey of sediments as consolidated rocks, distinct (with a few exceptions) from those composed of incoherent materials, some system of classification as a basis of discussion becomes essential. This task, however, is by no means an easy one, as most petrologists seem to have discovered. The difficulty of establishing a philosophical classification of sedimentary rocks is unquestionably greater than in the case of igneous rocks. No really satisfactory qualitative scheme has yet been evolved which makes due allowance for the innumerable transitional varieties prevalent; while a quantitative classification, temptingly foreshadowed by some possible adaptation of mechanical analysis, is still denied to the present state of knowledge.

Intimately bound up with this is the regrettably empirical nomenclature perforce adopted in the absence of something more fundamental than mere descriptive terms. In the light of modern research on both mineralogical and mechanical constitution of "sandstones," for instance, that term *per se* has ceased to have any really precise meaning. "Clay" is little better in this respect (though the old tendency to consider it synonymous with "kaolin" has at last been overcome), while "marl," "loam" and "silt" are notoriously subject to the widest interpretations.

* For completeness and convenience certain semi-consolidated and incoherent raw materials, *e.g.*, clay, ooze, abyssal mud, etc., are included in this chapter. The petrology of sand is sufficiently discussed elsewhere in this volume to render repetition unnecessary.

In the following paragraphs, an attempt is made to give as precise definitions of the conventional sedimentary rock-types as are possible, admittedly without breaking away very much from prevailing custom. In the present state of knowledge, probably the time is hardly ripe for drastic alteration, but the author would be failing in his duty if he did not voice in this place something of that feeling of discontent to which most contemporary workers on sedimentary rocks admit in regard to classification and nomenclature.

In view of the importance of "thin section" correlation of compact rock-types in exploitation oil-geology (discussed in Chapter VIII), it will be found that their treatment here departs from custom in its bias to the technique implied by that particular application. The rock is not merely described, it is analysed, especially in mineralogical, mechanical and *structural* detail; comparative features are stressed; contrast in specific detail rather than in group-character is emphasized.

Thin section correlation has taught at least one thing: discernment of and discrimination between the finer points of varietal characters of sedimentary rock-types; the criticism may be urged that this is carrying even intensive study too far. The reply to that is the enormous amount of successful work along these lines already accomplished in many field-laboratories, and the undoubted gain to the science in consequence. Sedimentary rocks are just as worthy of minute attention to detail as their igneous counterparts; when freely accorded their due in this respect, we may confidently expect that measure of enhanced interest from which advancement of knowledge alone can spring.

* * * * *

CLASSIFICATION OF SEDIMENTARY ROCKS.

GROUP CHARACTER.		TYPES.
A. Mechanical Origin	A1. Rudaceous	A1. 1. Conglomerate (p. 268).
		A1. 2. Breccia (p. 270).
	A2. Arenaceous	A2. 1. Sandstone (p. 273).
		A2. 2. Grit (p. 276).
		A2. 3. Arkose (p. 278).
		A2. 4. Quartzite (p. 279).
		A2. 5. Gnistier (p. 280).
		A2. 6. "Greywacke" (p. 281).
		A2. 7. Siltstone (p. 282).
	A3. Argillaceous	A3. 1. Clay (p. 286).
A3. 2. Fireclay (p. 290).		
A3. 3. Fullers Earth (p. 291).		
A3. 4. Æolian Clay (p. 292).		
A3. 5. Abyssal Clay (p. 294).		
A3. 6. Volcanic Clay (p. 295).		
A3. 7. Residual Clay (p. 297).		
A3. 8. Mudstone (p. 299).		
A3. 9. Shale (p. 300).		
↓		
AB. Calcareo-Argillaceous		AB. 1. Marl (p. 302).
		AB. 2. Calcareous Shale (p. 303).
B. Organic Origin	B1. Calcareous	B1. 1. Limestone (p. 307).
		B1. 2. Dolomitic Limestone (p. 312).
		B1. 3. Oolitic & Pisolitic Limestone (p. 314).
		B1. 4. Abyssal Ooze (p. 316).
		B1. 5. Chalk (p. 317).
	B2. Siliceous	B2. 1. Chert & Flint (<i>in part</i>) (p. 320).
		B2. 2. Abyssal Ooze (p. 321).
		B2. 3. Siliceous Earth (p. 322).
	B3. Ferruginous	B3. Ferruginous Deposits (p. 325), see also under (C2) (p. 349).
	B4. Carbonaceous	B4. 1. Peat (p. 328).
		B4. 2. Lignite (p. 329).
		B4. 3. Coal & Anthracite (p. 330).
		B4. 4. Cannel & Torbanite (p. 334).
		B4. 5. Oil Shale (p. 336).
		B4. 6. Asphalt & Asphaltic Impregnations (p. 337).
B5. Phosphatic	B5. Phosphate (p. 341).	

GROUP CHARACTER.		TYPES.	
C. Chemical Origin	C1. Calcareous	C1. 1.	Calcium Carbonate : Calcite (p. 346).
		C1. 2.	Dolomite (<i>in part</i>) (p. 347).
	C2. Ferruginous	C2. 1.	Bedded Iron-Ores (p. 349).
		C2. 2.	Bog Iron-Ore (p. 352).
	C3. Siliceous	C3. 1.	Siliceous Sinter (p. 353).
	C4. Saline	C4. 1.	Chlorides (p. 355).
		C4. 2.	Sulphates (p. 356).
		C4. 3.	Nitrates & Borates (p. 359).

As in most branches of natural history, origin alone forms the soundest basis of classification, and this starting point is almost universally adopted in the case of sedimentary rocks. Thus the primary division is :—

(A) MECHANICAL ORIGIN (p. 267).

(B) ORGANIC ORIGIN (p. 305).

(C) CHEMICAL ORIGIN (p. 344).

(A) MECHANICAL ORIGIN. This implies the action of gravity and/or transport by wind, water or ice with subsequent deposition. The predominant character is initially incoherency, the individual particle varying from the ultra-microscopic or colloidal, to the largest boulder, subsequently (with the process of time) consolidation by various cementing media. Raw materials are essentially pre-existing rock-fragments released during the normal progress of erosion. These are the “derived” or “allogenic” constituents (“allothigenous” of some authors). The cementing media, products of mineral destabilisation, organic or chemical agency, operate during or subsequent to the deposition phase; these are the “authigenic” constituents (“authigenous” of some authors).

Rocks in this category may be subdivided into three main groups on the basis of average grade-size, *i.e.*, major dimension or diameter of predominant rock-fragment or particle (p. 108):—

(A1) RUDACEOUS (p. 268).

(A2) ARENACEOUS (p. 273).

(A3) ARGILLACEOUS (p. 284).

(A1) RUDACEOUS DEPOSITS. These include rocks composed of “granules,” “pebbles,” “cobbles” or “boulders” (p. 110), *i.e.*, of materials exceeding 2 mm. in grade-size of predominant constituent. Talus and cliff debris, avalanche material (the “colluvial” deposits of Merrill), scree, shingle and gravel contribute the aggregates which, on consolidation, form either of two rock-types:—

(A1. 1) Conglomerate (p. 268).

(A1. 2) Breccia (p. 270).

(A1. 1) **CONGLOMERATE.**

[Fig. 75

**Lith.* Appearance of consolidated gravel. Bedding rare

* In order to abbreviate and systematize descriptions, rock-types are discussed under specific property “headings.” *Lith.*=lithology, *i.e.*, appearance to the naked eye, megascopic characters, macro-structure, colour, etc. *Text.*=texture, either of whole rock if uniform, or of prominent components and matrix. *Shape* has reference to shape of predominant constituents, expressed as R, rounded, SA, subangular, or A, angular. *Min. Comp.*=mineralogical composition, divided into *Al.*, allogenic, and *Au.*, authigenic constituents. *Mech. Comp.*=mechanical composition (limiting grades for the type are given). *Micro.*=micro-structure as determined from microscopical study. *Types*, usually of British origin, are given to illustrate the rock under discussion; the selection has been specially made from accessible occurrences in order that the student, if he wishes, may collect or otherwise acquire these representative examples for study. Appropriate references (*Ref.*) are added.

or absent. Colour variable, determined largely by matrix.

Text. Coarse. Matrix fine (cryptocrystalline), or sandy.

Shape. R to SA (ellipsoidal) pebbles.

Min. Comp. Al. Pebbles of quartz, quartzite, vein-quartz, chalcedonic silica, flint, chert; occasionally other rocks, including igneous. Accessory minerals scarce, usually absent from matrix, recoverable from pebbles by crushing.

Au. Silica, limonite, hæmatite; less commonly calcite, dolomite. Cement not only binds pebbles together, but sometimes penetrates cracks in them.

Mech. Comp. Minimum grade > 2 mm. Usual types 0.75-2.5 cms. Generally variable. (Matrix cryptocrystalline.)

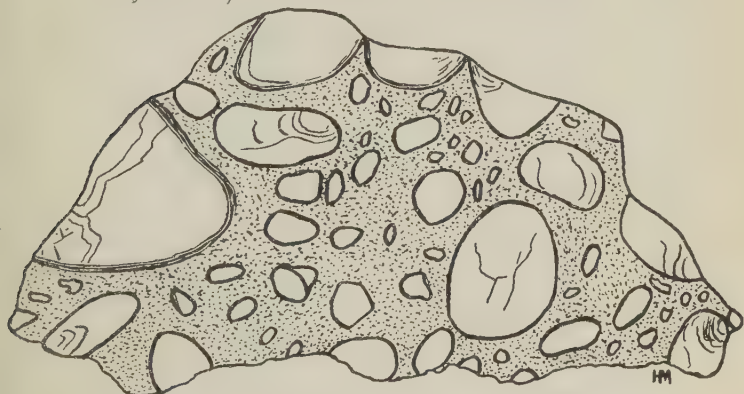


FIG. 75. Drawing of smooth surface of Flint Conglomerate (Hertfordshire "Pudding Stone"). [$\frac{1}{2}$ Nat. Size.]

Micro. Study relationship of pebbles to matrix: note boundary and whether both are in optical continuity (rare) or not; matrix normally fills interstices completely, especially in finer varieties. Quartz pebbles may be clear or turbid with inclusions: the latter are significant and may indicate origin (p. 428), undulose extinction due to strain sometimes noted. Chert exhibits aggregate polarisation; flint is usually cryptocrystalline or optically inert. Silica cement usually cryptocrystalline, but may be slightly coarser towards

centre of interspace. Presence of calcite shown by "twinkling" and contrasted interference colour. White mica characteristic of some varieties. Presence of dolomite usually inferred from chemical test. Matrix may be contaminated with finer detritus, volcanic dust, also with minerals, e.g., pyrite, gold.

Types. Cambrian conglomerate of quartz, quartzite, felsite, schist, granite, etc., of Pre-Cambrian origin in siliceous and ashy matrix, St. Davids, South Wales;¹ the Bunter Pebble Bed, with chocolate-coloured quartzite, Carboniferous Limestone, purple grit and volcanic rocks in siliceous or calcareous matrix, Midland counties;² "Dolomitic Conglomerate," chiefly Carboniferous Limestone pebbles from 2" up to boulders 3' in diameter, set in a calcareo-dolomitic cement, of the Mendip and Bristol Channel area (Trias);³ Eocene "pudding stone" of Hertfordshire and Kent, mostly quartz pebbles in cryptocrystalline, siliceous matrix (fig. 75).⁴

Ref. ¹ H. Hicks, *Q.J.G.S.*, xxvii., 1871, p. 386.

² T. G. Bonney, *Q.J.G.S.*, lvi., 1900, p. 287.

³ A. J. Jukes-Browne, *Stratigraphical Geology*, 1912, p. 366.

⁴ J. Hopkinson, *Geol. Assoc. Jubilee Vol.*, 1910, p. 16.

(AI. 2) BRECCIA.

[Fig. 76]

Lith. Rock-fragments of distinctive shape and miscellaneous size set in a matrix of mixed character and composition. Fragments may be of the same rock or dissimilar according to uniformity or variation of parent-rocks. Bedding rare. Norton¹ recognizes four megascopic types:—"crackle breccia," representing incipient brecciation, with fragments parted by fission-planes, but subject to little or no displacement; such fragments "match" along their opposed sides; matrix confined to interstices and is usually of chemical origin. The "mosaic" type has its fragments largely disjointed and displaced. "Rubble breccia" exemplifies the type "in which no matching fragments are parted by initial planes of rupture. The fragments are close-set and in touch." The "breccia of sporadic fragments" is the type in which the matrix preponderates over fragments which are "like plums in a pudding." Where the matrix is bedded, the breccia belongs to the

¹ W. H. Norton, *Journ. Geol.*, xxv., 1917, p. 161.

"*endostratic*" type, of which some of the Permian "*breccia sandstones*" are examples.¹ In fossiliferous breccias, fossils may occur both in fragments and in matrix, but usually the latter. Contemporaneous brecciation with deposition gives rise to "*intraformational breccias*" (Walcott).



FIG. 76. Breccia with calcite fragments, etc.

Text. Coarse, determined by the size of the fragments.

Matrix usually fine, like mud, or gritty.

Shape. A. Fragments sometimes show signs of attrition acquired during local transport. Particles in matrix both A and SA.

Min. Comp. Al. Any rock-type is likely to contribute, given the requisite conditions; even the softest rocks

¹ W. W. King, *Q.J.G.S.*, lv., 1899, p. 105.

may, as fragments, survive in breccias in which little or no transport has been involved.

Au. Matrix may be composed of pulverized rocks represented as fragments, or may be of different origin; fine silt or mud; chemical deposit, *e.g.*, calcite, limonite. Usually very mixed in composition.

Mech. Comp. Minimum grade >2 mm. Usual types 0.5-3.0 cms., maximum length of fragment; but much larger fragments may occur, even huge blocks weighing several tons each. Matrix composed of particles <0.01 mm. in the finest muddy types, ranging up to 1 mm. in the gritty types.

Micro. Study relationship of fragments to matrix; note boundaries and extent to which matrix forms seams or fills interspaces. Proportion of matrix to fragments important; in some types the latter predominate, in others the matrix is more conspicuous than the fragments (see above). Diagnose coarse constituents and note variety of rock-types represented; if one predominating type is found, note to what extent its characteristic minerals have contributed to the matrix. Composite or simple character of the fragments also important. Examine matrix for rock-particles and individual minerals, also for alteration products and special cementing media of chemical origin. Cementing materials, where contaminated with rock-powder, usually require long and careful scrutiny to establish complete diagnosis. Shell-fragments noted in fossiliferous varieties.

Types. Permian breccias in the Penrith Sandstone, Eden Valley, Cumberland, etc., "The Brockrams"; one type (lower) is made up of Carboniferous Limestone fragments in a red sandy matrix; the other (upper) contains fragments of basal Carboniferous conglomerate reinforced by Ordovician rocks, vein-quartz, etc.¹ Upper Permian breccias of the Midlands, "Trappoid Breccias," in which the fragments are mainly of volcanic origin (old field-term "trap"), with quartzites, sandstone and limestone of Pre-Cambrian, Cambrian, Ordovician and Silurian origin.²

Ref. ¹ A. J. Jukes-Browne, *Stratigraphical Geology*, 1912, p. 337.

² W. W. King, *op. cit.*

See paper by Norton for further references; also S. H. Reynolds, "Breccias," *Geol. Mag.*, lxx., 1928, p. 97.

(A₂) ARENACEOUS DEPOSITS. These are the true clastic accumulations and include sands, sandstones, silts, etc., whose component particles fall between the size-limits 0.01 and 2 mm. (p. 108); the conventional silt grade-limits are 0.1 mm.-0.01 mm.; the consolidated form, siltstone, is sometimes separated as a distinct group.¹ Since, however, this constitutes a specific rock-type rather than a group comparable in importance with other mechanically-formed deposits (A₁, A₃), it is here classified under arenaceous deposits. The raw materials are essentially sand,² rainwash, etc., and these on consolidation give rise to the following types:—

- (A₂. 1) Sandstone (p. 273).
- (A₂. 2) Grit (p. 276).
- (A₂. 3) Arkose (p. 278).
- (A₂. 4) Quartzite (p. 279).
- (A₂. 5) Ganister (p. 280).
- (A₂. 6) "Greywacke" (p. 281).
- (A₂. 7) Siltstone (p. 282).

(A₂. 1) **SANDSTONE.** [Figs. 77, & 78, 79, 81, Pl. xxiv.
Lith. Compounded essentially of derived quartz grains cemented by a matrix which may or may not be conspicuous. Predominantly siliceous, the purest varieties containing over 99.5% SiO₂. Bedding usually apparent, thin (laminæ) or thick, either regular, horizontal, or current- or cross-bedded. Colour determined largely by nature of cementing medium, the commonest being limonite (brown), hæmatite (red); highly siliceous types are white to colourless. Organic components common, often casts. Structural features include ripple-marks, veining, cross-joints, organic markings, rain-prints, sun-cracks, etc.

Text. Coarse (0.5 mm.-2 mm.), medium (0.25 mm.-0.5 mm.), and fine (0.1 mm.-0.25 mm.).

¹ G. W. Tyrrell, *Principles of Petrology*, 1926.

² See footnote, p. 264.

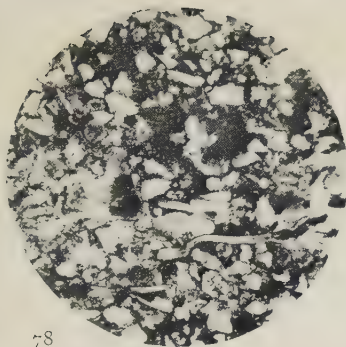
Shape. Generally SA (water-worn grains); R in wind-blown sand; A in glacial sand. Predominantly angular in Grit, A₂.

Min. Comp. Al. Quartz, muscovite, feldspar (see under Arkose, A₂. 3, p. 278); occasionally rock-particles of igneous or volcanic origin; accessory minerals such as ilmenite, magnetite, zircon, tourmaline, garnet, rutile, etc. (See ch. vi).

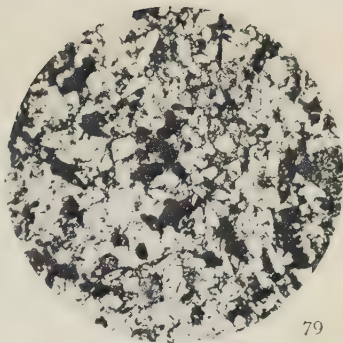
Au. Cementing materials include siliceous, ferruginous, calcareous, argillaceous, and carbonaceous matter, in that order of normal occurrence. More rarely barite.

Mech. Comp. Size-limits are 0.1 mm.-2 mm. ("sand grade"); average about 0.2 mm. If the sand is superfine (= coarse silt) the lower limit is 0.05 mm.

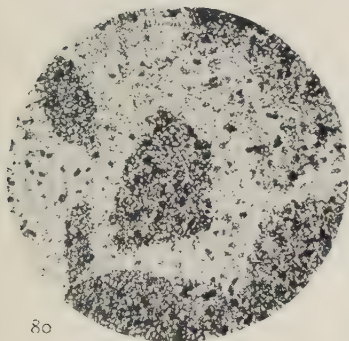
Micro. Study quartz grains for shape, dimensions (uniform or mixed), degree of preservation of crystallization (euhedrism), inclusions (p. 226) and optical character, *i.e.*, whether normal or undulose extinction. Muscovite detected by its irregular flaky character, cleavage and interference colours (pinks, greens and yellows). Other prominent constituents, *e.g.*, glauconite, should present no difficulty; accessory minerals best investigated by crushing and concentration (p. 73). Quartz grains may be mutually interferent, with little or no cementing matter, when the rock approximates to the quartzite type (A₂. 4); in most examples the matrix is clearly discernible, and limonite, hæmatite, calcite, silica, etc., will be easily determined. Differentiate between types in which each quartz grain is completely surrounded by cement; in which grains occur in clusters, many touching, the cement being haphazardly distributed; and those in which there is apparently more cement than derived matter. Relation of grains to cementing medium, especially peripheral contact, is important. Secondary outgrowths of silica from original quartz nuclei, each outgrowth being in optical continuity with its nucleus, are sometimes observed. Siliceous cement may be cryptocrystalline or microcrystalline. It is seldom that only one material constitutes the cement; calcite is detected by "twinkling," hæmatite and limonite by colour, likewise carbon. Calcareous cement may be anticipated where organisms prevail. Greenish cement is not necessarily due to glauconite, but more often to chlorite after ferromagnesian minerals. Clayey matter



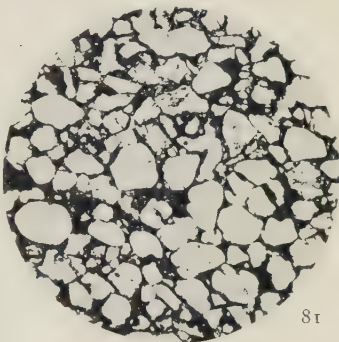
78



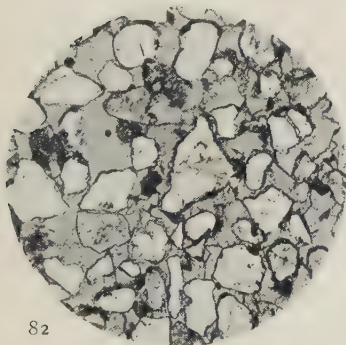
79



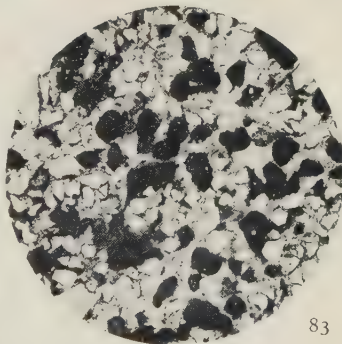
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81



82



83

SANDSTONE AND GRIT.

- FIG. 78. Hollybush Sandstone (Cambrian), Malvern. [x 30.]
 " 79. May Hill Sandstone (Silurian), Malvern. [x 30.]
 " 80. " Tilgate Stone," Calcareous Grit (Wealden), Sussex. [x 25.]
 " 81. Ferruginous Sandstone (Aptian), Betchworth, Surrey. [x 15.]
 " 82. Calcareous Grit (Aptian), Faringdon, Berks. [x 25.]
 " 83. Glauconitic Grit (Selbornian), Sutton Poyntz, Dorset. [x 15.]

To face page 274.

PLATE XXIV.

gives rise to a dirty brown, almost indecipherable cement, though usually micaceous. Gypsum, barite, dolomite, are uncommon authigenic constituents, but are not hard to identify.

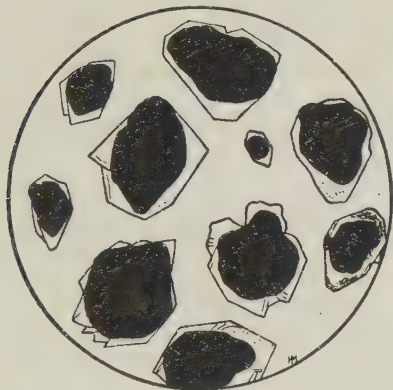


FIG. 77. Grains from the Penrith Sandstone (Permian), Cumberland, showing secondary outgrowths of quartz. [x 25.]

Types. Hollybush Sandstone (Cambrian) of Malvern, etc., a mica-glaucanite-bearing rock;¹ Bala Sandstone of the Welsh Borders (Ordovician), a ferruginous, micaceous type with many shell-casts; Old Red Sandstone, Herefordshire and South Wales, with hæmatite cement;² Permian Sandstone, Penrith, Cumberland (fig. 77), with beautiful crystal outgrowths in optical continuity with nuclei (desert sand);³ Triassic Sandstone, Alderley Edge, Cheshire, with barite cement and impregnations of azurite, malachite, galena, etc.; Ashdown Sand (Wealden), Fairlight, Sussex, pure white "glass" sandstone;⁴ Lower Greensand, Faringdon, Berkshire, with glauconite, sponge remains, and calcite "platy" cement enveloping sand grains in "ophitic" fashion; Lower Greensand, Ightham, Kent ("Ightham Stone"), with radial, chalcedonic cement enclosing grains;⁵ Lower Greensand ("Carstone"), Hunstanton, Norfolk, and Yorkshire, with heavy ferruginous cement and oolitic grains of iron-ore with siliceous

skeleton (on treatment with acid);⁶ Upper Greensand, Sutton Poyntz, Dorset, glauconitic sandstone (glauconite casts of *foraminifera*) with siliceous and calcareous cement; Eocene Sandstone ("Sarsens"), chalk downs of Wiltshire, Dorset, etc., fine micaceous rock graduating to quartzite type;⁷ Bagshot Sand, Studland, etc., Dorset, deep reddish-brown, ferruginous sandstone and variegated types.

Ref. ¹ G. S. Sweeting, *Proc. Geol. Assoc.*, xxxviii., 1927, pp. 552-556.

² A. Heard & R. Davies, *Q.J.G.S.*, lxxx., 1924, p. 489.

³ A. Harker, *Petrology for Students*, 1919, p. 212 & fig. 72, F.

⁴ P. G. H. Boswell, *British Resources of Sands for Glass-Making*, 1918, pp. 52-54.

⁵ T. G. Bonney, *Geol. Mag.*, 1888, pp. 297-300.

⁶ H. C. Versey & C. Carter, *Proc. Yorks. Geol. Soc.*, xx., 1926, p. 349; also A. Harker, *op. cit.*, p. 212.

⁷ H. B. Woodward, *Geol. Assoc. Jubilee Vol.*, 1910, pp. 304-5.

For Upper Cretaceous sandstones of England, see W. Hill, *Mem. Geol. Surv., Cret. Rocks Brit.*, vol. i., 1900, ch. xxv.

(A2. 2) **GRIT.**

[Figs. 80, 82, 83, Pl. xxiv.]

Lith. The separation of this type from normal sandstone depends on the angularity of the quartz particles, a feature not always apparent from megascopic examination. Every gradation from grits, in which the particles are equidimensional, through pebble-grits, to conglomerates (A1. 1) is met with. In the coarse varieties prominent constituents are identifiable with the naked eye (chiefly quartz, quartzite). Stratification normally developed on a large scale and may not be apparent in the hand-specimen. Colour variable but usually yellow, buff, brown or grey. Organic remains may be present in the medium and fine varieties, less frequently in the coarse types. Prominent pebbles should be extracted and dealt with separately.

Text. Coarse to medium.

Shape. A.

Min. Comp. *Al.* Quartz; composite grains of quartz and felspar, muscovite, particles of igneous, volcanic and metamorphic origin; also of the harder sedimentary

rock-types; quartzite; also vein-quartz. Stable accessory "heavy" minerals.

Au. Siliceous, calcareous, ferruginous and argillaceous cements; the first two materials are commonest. Micaceous and chloritic matter often prevalent.

Mech. Comp. Size-limits of derived particles in true grits fall between 0.1 mm.-2 mm. Above the latter grade the rock passes into a fine conglomerate (*q.v.*). Many types described as grits are mechanically classifiable under the latter heading, especially when pebbles occur.

Micro. Microscopical examination reveals at once the angularity of the predominant grains, though some degree of rounding is nearly always apparent. Inclusions in the quartz grains noteworthy. Most examples show mixed composition and present interesting problems in the identification of components. In certain calcareous grits "lustre-mottling" is a striking feature, sometimes seen in the hand-specimen, but more conspicuous in thin section. "When the polariser is in position . . . the differential relief ("twinkling" effect) characteristic of the rhombohedral carbonates resolves the field into areas within each of which the calcite cementing the quartz grains is in crystallographic continuity . . . lustre-mottling . . . is due to the reflection of light from the calcite cleavages which are differently orientated."⁶

Other points in diagnosis as for Sandstones (*q.v.*).

Types. Ingletonian Grit of Yorkshire, with grains of gneiss, lava, etc., in addition to quartz, feldspar, mica;¹ Watch Hill Grit (Bala) of Cumberland, with vein-quartz, carbonaceous shale, spilosite, composite quartz-feldspar fragments, schist, and granophyre (from Carrock Fell complex) with quartzose, feldspathic, micaceous and silty matrix;² Staddon Grits (Devonian) of South Devon, etc., purplish-red, with siliceous and calcareous cements;³ Millstone Grit of Yorkshire, notable specially for quartz inclusions, pebbles, and accessory minerals;⁴ Inferior Oolite ("Moor Grit"), Yorkshire, tending to quartzite type;⁵ "Tilgate Stone" (calcareous grit with "lustre-mottling"), Wadhurst Clay (Wealden), Sussex.⁶

Ref. ¹ R. H. Rastall, *Proc. Yorks. Geol. Soc.*, xvi., 1906, pp. 94-98.

² J. F. N. Green, *Proc. Geol. Assoc.*, xxviii., 1917, p. 21.

³ W. G. Shannon, *Proc. Geol. Assoc.*, xxxix., 1928, p.

144.

⁴ A. Gilligan, *Q.J.G.S.*, lxxv., 1919, p. 251.

⁵ A. Harker, *Petrology for Students*, 1919, p. 210.

⁶ G. S. Sweeting, *Proc. Geol. Assoc.*, xxxvi., 1925, pp.

413-4.

N.B.—“*Pea Grit*,” “*Trigonia Grit*,” etc., are not true grits (p. 316).

(A2. 3) **ARKOSE.**

[Fig. 84, Pl. xxv.]

Lith. Comparable with either sandstone or grit, generally the latter. A type separated to designate a feldspathic sandstone or grit derived from granitoid or gneissic rocks and containing prolific feldspar, the latter usually only determinable under the microscope. Colour often pale red or purple, but may vary. White mica usually prominent.

Text. Coarse to medium.

Shape. A to SA.

Min. Comp. *Al.* Quartz, feldspar (microcline, orthoclase, plagioclase, micropertite, etc.), muscovite; rock-fragments of miscellaneous origin; iron-ores and stable accessory minerals.

Au. Siliceous, calcareous, feldspathic, hæmatite and limonite; greenish colour due to chlorite and, or epidote; occasionally carbonaceous.

Mech. Comp. As for sandstone and grit (*q.v.*).

Micro. The chief study in these rocks is the feldspar, of which microcline and oligoclase appear to be the commonest constituents. Note relative proportions of quartz and feldspar grains. Determine carefully the optical properties of the feldspars present. Much of the quartz may show strain-polarisation effects. Quartz and feldspar grains may be in mutually interferent aggregates surrounded by cementing medium, or each grain may be enveloped in a thin film of iron oxide; in the less coloured varieties, silica and/or calcite cement is common. Arkoses generally approximate to the quartzite type (A2. 4) and are highly siliceous. Nature and degree of distribution of derived grains in cement important and diagnostic. Other criteria as for sandstone, grit.

Types. Torridonian rocks of the N.W. Highlands, with various feldspars, distinctive quartz, and pebbles of more ancient rocks;¹ Millstone Grit of Yorkshire.²

- Ref. ¹ J. J. H. Teall, *Geology N.W. Highlands, Mem. Geol. Surv.*, 1907, ch. xvi. (an excellent and exhaustive account of this rock-type).
² A. Gilligan, *Q.J.G.S.*, lxxv., 1919, p. 251.

(Az. 4) **QUARTZITE.** [Figs. 85-87, Pl. xxv.

Lith. Distinguish from quartzite of metamorphic origin. The sedimentary type consists almost exclusively of quartz grains set in a siliceous cement. Normally a pale-coloured, close-grained or "sugary" rock of obvious siliceous character. Impurities may be rock-fragments visible to the naked eye, ferruginous matter, mica, etc. Quartz is often water-clear. Bedding generally only apparent on a large scale. Organisms not common.

Text. Coarse to medium; in special types, very fine (cf. Az. 5.).

Shape. SA.

Min. Comp. Al. Quartz, subordinate feldspar, mica, few accessory minerals.

Au. Silica, sometimes with finely disseminated iron oxide; less commonly carbonaceous and silty matter.

Mech. Comp. Average of many examples shows detrital grains of grade-size between 0.2 mm. and 0.3 mm., i.e., of medium grade.

Micro. Under the microscope quartzites present characteristic mosaic appearance, quartz grains closely set in a clear siliceous cement; with passage of the rock to less pure sandstone, the grains tend to be more scattered and the cement more prominent. Quartzitic cement may be granular. In some examples it develops directly from detrital nuclei by crystalline outgrowths, sometimes in optical continuity. Occasionally cement is clouded by finely divided silty matter or dust; calcite not common. White mica prevalent and, in certain cases, feldspar in sufficient quantity to designate the rock an arkose. Note particularly the size and shape of the quartz grains, any inclusions, unusual optical properties, also the relationship of grains to matrix. Distinguish sedimentary quartzite from metamorphosed sandstone by the fact that in the latter there is practically no differentiation of detrital grains and matrix, the whole being a homogeneous quartzose rock of mutually interferent quartz pellicles.

Types. Pre-Cambrian quartzite, Islay, Jura, etc., Argyllshire, fine-grained saccharoidal type;¹ Dalradian Quartzite (Pre-Cambrian), Kentallen, Argyllshire, with little micropertthite, pyrite and a minimum of siliceous cement; Appin Quartzite from same region, similar; Hartshill Quartzite (Pre-Cambrian) of Warwickshire, a pinkish compact type with somewhat worn quartz grains, a little felspar, chlorite and epidote after ferromagnesian minerals and siliceous cement, in many cases recrystallised about detrital grains;² Stiperstones Quartzite (Ordovician), Shropshire, with mica and silty siliceous cement;³ Estuarine quartzites, Comondale, Glaisdale, Castleton, etc., Yorkshire, compact types with cryptocrystalline ground-mass.⁴ See also under "Ganister" (Az. 5, below).

Ref. ¹ H. H. Thomas, *Mem. Geol. Surv., Spec. Rep. Min. Resources, Gt. Brit.*, xvi., 1920, p. 13, etc.

² W. W. Watts, *Summ. of Progress Geol. Surv.*, 1897, p. 68, & *Proc. Geol. Assoc.*, xv., 1898, pp. 393, 397.

³ A. Harker, *Petrology for Students*, 1919, pp. 209, 214.

⁴ H. H. Thomas, *op. cit.*, p. 13, pl. 2, fig. 3.

(Az. 5) **GANISTER.**

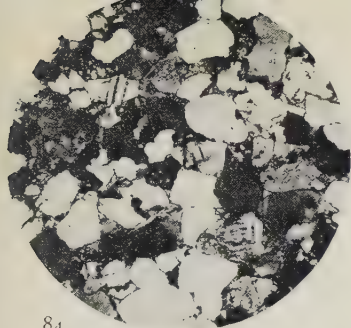
[Fig. 88, Pl. xxv.]

Lith. In its strict interpretation ganister is a particular kind of highly siliceous rock, a variety of quartzite, comparable with the "Sheffield Ganister," a well-known refractory material occurring in the Ganister group of the Lower Coal Measures. There are many varieties, from the true quartzose rock to the less pure "bastard ganister" and "silica rock." Ganister is normally hard, very compact, uniform, and of a grey colour, sometimes streaked with carbonaceous matter. Bedding seldom observed in small specimens. Fracture is characteristic, yielding smooth, subconchoidal grooves and hollows; newly broken edges very sharp. Some types have the appearance of "hornstone." Dark coloured types usually denote considerable impurity and are seldom true ganisters.

Text. Homogeneous, compact, fine-grained; sometimes granular or saccharoidal.

Shape. SA.

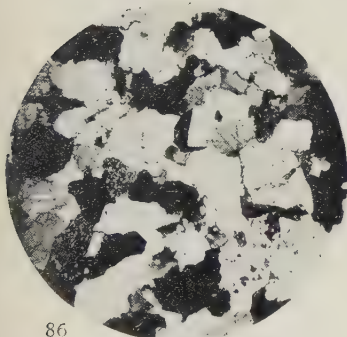
Min. Comp. Al. Quartz, chert, felspar, mica, and stable accessory minerals, e.g., iron-ores, tourmaline, rutile, anatase.



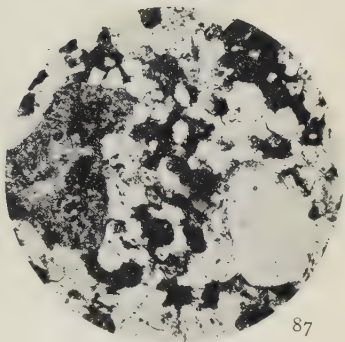
84



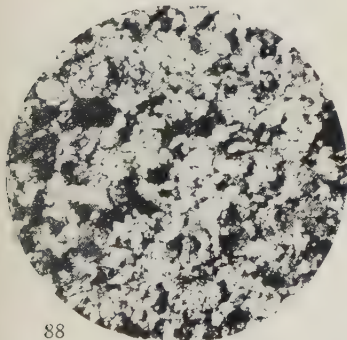
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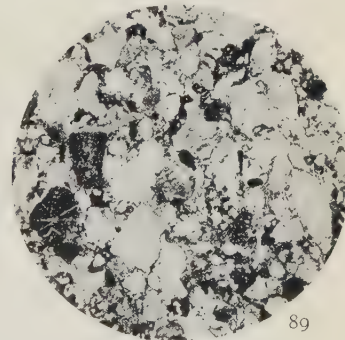
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87



88



89

ARKOSE, QUARTZITE AND GREYWACKE.

- FIG. 84. Torridon Sandstone (Arkose), Loch Torridon, Ross.* [x 25.]
 „ 85. Quartzite (Archæan), Kentallen, Argyllshire.* [x 18.]
 „ 86. Hartshill Quartzite (Cambrian), Nuneaton.* [x 18.]
 „ 87. Malvern Quartzite (Cambrian), Gullet Pass, Malvern. [x 25.]
 „ 88. Ganister (Coal Measures), Sheffield, Yorks.* [x 25.]
 „ 89. "Greywacke" (? Carboniferous), Richmond Boring, London
 (1150 ft.). [x 25.]

To face page 280.

[*Crossed Nicols.]

PLATE XXV.

Au. Silica, hæmatite, limonite, kaolinite, sericitic mica, clayey matter.

Mech. Comp. Average grade-size 0.05 mm.-0.15 mm. Coarser types up to 0.25 mm. Sometimes very small interstitial grains 0.02 mm. observed. Extremely coarse types are grits.

Micro. Normal rock consists of a mosaic of quartz grains often remarkably uniform in shape and size. These may be closely packed, giving rise to an interlocking structure, or the siliceous cement may be quite conspicuous. Where grains vary in size, the smaller pack together between the larger. In the purest types only siliceous cement is observed, though very finely divided carbonaceous dust may permeate it. This cement is usually cryptocrystalline, often chalcedonic. Network of cracks may traverse the rock, filled with silica, limonite, rarely with calcite.

Types. Lower Carboniferous, Sheffield Ganister ("Hard Mine"), the type rock; another variety from Deepcar is saccharoidal and streaked with carbonaceous matter;¹ another from Huddersfield contains abundant mica and rutile; the Hawksworth Ganister ("Guiseley Rock") is a very pure type.² So-called "bastard" ganisters are petrologically either impure quartzites, or sandstones and grits.

Ref. ¹ *Mem. Geol. Surv., Spec. Rep. Min. Resources Gt. Brit.*, vi., 1920, p. 23.

² *Op. cit.*, p. 32.

For general account of petrography of ganister, silica rocks, etc., see H. H. Thomas, *Mem. Geol. Surv., Spec. Min. Resources Gt. Brit.*, xvi., 1920.

(A2. 6) **GREYWACKE.**

[Fig. 89, Pl. xxv.

Lith. An old field-term which has been usefully revived to designate arenaceous rocks of a peculiar type, specially developed in British palæozoic formations. Essentially a sandstone compounded of quartz and miscellaneous rock-particles of diverse origin, the latter often in excess of the detrital quartz. The very mixed character of these rocks is usually discernible at a glance, while the grey, green or darker colour is common. Often highly micaceous, well bedded, usually void of recognizable organic remains.

Text. Coarse to medium, "gritty."

Shape. A.

Min. Comp. *Al.* Rock-particles include fragments of basic rocks, slates, sandstones, and volcanic lavas. Quartz, chert, quartzite, mica, iron-ores and usually scanty accessory minerals.

Au. Silica, ferruginous, chloritic and argillaceous matter.

Mech. Comp. Variable from sand-grade to much coarser material (rudaceous).

Micro. The microscopic study of these rocks is somewhat similar to that of breccias, only on a much smaller scale. The student has to be prepared for practically any rock-type in the form of small or large grains or flakes, and a knowledge of the locality and geologic history of the rock under investigation helps considerably in determining the nature of the derived fragments present. Quartz presents no difficulties by itself, but the cementing material, being often packed full of fine rock-dust, is difficult of identification. Usually decomposition products such as mica, chlorite, kaolinite, epidote, sometimes serpentine, are conspicuous. These rocks are for the most part structureless, and exhibit a heterogeneous constitution of marked variation from one example to another.

Types. Ordovician "greywacke" of Montgomeryshire, with abundant volcanic inclusions; Old Red Sandstone, Welsh Borders, purplish-grey, brown and greenish types with plutonic, volcanic and sedimentary rock-particles.¹

Ref. ¹ G. W. Tyrrell, *Principles of Petrology*, 1926, pp. 209-10.

(A2. 7) **SILTSTONE.**

Lith. This type has been separated by J. F. N. Green¹ to comprise those rocks which are essentially compacted silts, conforming in grade to the latter raw material. They are principally products of fluvial, lacustrine, glacial and æolian action, in other circumstances of volcanic origin, and usually present distinctive features. The fine sandy character is typical, together with perfect lamination in the aqueous types. Such lamination may be picked out by different coloured iron-oxide films, depending on the degree of impregnation developed from plane to plane. Fine current-bedding and ripple-marking are also observed in some types.

¹ Ref. ¹, page 284.

Organic remains are common, especially carbonaceous plant-fragments. Colour normally grey, buff or brown except in the æolian types, when hæmatite staining may be prominent. Siltstones frequently illustrate the phenomenon of rhythmic banding, especially those of lacustrine origin.

Text. Essentially fine textured, close grained and compact; some varieties earthy.

Shape. SA in all except æolian types, the latter SA to R.
Min. Comp. Al. Quartz, muscovite, felspar, iron-ores and miscellaneous accessory minerals. Siltstones as a rule yield a fair quantity of heavy residue.

Au. Siliceous, ferruginous and calcareous cement; carbonaceous dust often present. Much of the irresolvable matter is clay.

Mech. Comp. Particles fall between the size-limits 0.01 mm. and 0.1 mm. Average about 0.06 mm.

Micro. In finely laminated varieties study by means of sections cut both parallel and transverse to lamination. The former exhibits a mass of fine quartz particles with cementing matter enveloping each, or clustered aggregates giving a patchy mosaic structure; this type of section should also show the relationship of the matrix to the detrital particles, the character of any organisms present, and especially the development of mica. The transverse section exhibits some degree of parallelism of the component minerals, variations in these from plane to plane, and longitudinal sections of any organisms present, *i.e.*, those reposing normally with the bedding. In many examples the manner of impregnation of the authigenic matter is best studied from these transverse sections. Much of the cement, if argillaceous, may be difficult to decipher, and may also prove optically inert, owing to its extremely finely divided state (see A3., p. 284). Miscellaneous rock-particles, composite or simple in character, prevail in some examples, thus allying the type with the "greywackes" (A2. 6, p. 281). The presence of calcite is frequent and is usually easily detected.

Types. Silurian of North Wales; also Lake District;¹ Old Red Sandstone, Caithness, N.B., slaty "flagstones" with abundant lime and organic matter;² Keuper silts and marls, Leicestershire; Ashdown Sand (Wealden), Sussex, siltstones of fluvatile origin, finely laminated, ferruginous cement, with plant remains.

ostracods, etc.; Weald Clay siltstone (Wealden), Hordsham, Sussex, with calcareous cement, lignite, etc.

Ref. ¹ J. F. N. Green, in A. Holmes, *Nomenclature of Petrology*, 2nd ed., 1929, "Siltstone," p. 211.

² *Mem. Geol. Surv. Scotland, Geology of Caithness*. 1914, pp. 89-97.

(A3) ARGILLACEOUS DEPOSITS. This division comprises all the finest mechanically-formed sediments, represented essentially by clays and those rock-types produced therefrom by consolidation and by expression of moisture. The constituent particles range from an upper limit of 0.01 mm. in diameter to ultra-microscopic and colloidal matter. Of all sediments, these are the most difficult to investigate thoroughly from a petrological standpoint, owing to the finely divided state of their components, and also because of the difficulty of determining mineralogically much of the authigenic matter which, as "clay paste," defies diagnosis by microscopical means alone.

Recent research has shown that at all events kaolinite does not play the supreme part in constitution of these rocks as formerly imagined; only in certain restricted types is this mineral really prevalent. Much of the modern work on soils (Chapter XI) has thrown a flood of light on the real composition of argillaceous rocks, and the recognition of the role of the "colloidal complex," mostly attributable to various forms of aluminous silicate and hydrated compounds, is a definite step towards their better understanding. In another direction, chemical and physical analysis of various clays suited to particular purposes in the arts, has led to certain definite conclusions on mineralogical composition. The work of C. S. Ross and E. V. Shannon on bentonite,¹ for instance, is a distinct advance and an inspiration to similar research on

¹ *Journ. Amer. Ceramic Soc.*, ix., 1926, pp. 77-96.

other types of clay, hence of the consolidated rocks to which it gives rise. This will be again referred to in what follows.

The petrology of argillaceous rocks owes much in recent years to the necessitous study of clays for refractory purposes; but it must be admitted that lack of organized knowledge leading to co-ordination of all the data collected, has resulted in the distinction of innumerable types, in most cases more confusing than progressive. Several attempts have been made to bring these varied types within a comprehensive scheme of classification, especially in America; such classifications have depended either upon origin, chemical analysis, physical properties, or on their behaviour under conditions of heat or desiccation. As with attempts at mineralogical classification of clays, none of these has yet succeeded in bringing within a convenient compass all varieties known, or in framing a logical scheme as a basis of petrological analysis and description. Thus, although argillaceous rocks in general, and clays in particular, enjoy a literature far outweighing in bulk that available in connexion with any other sediments, descriptions are still in most cases rather arbitrary and biassed according to the particular angle from which the writer happens to be viewing the subject: witness the classifications enunciated by Orton,¹ Wheeler,² Ladd,³ Buckley,⁴ Grimsley and Grout,⁵ Ries,⁶ and Searle.⁷

The author has confined himself in this volume to those varieties of argillaceous rocks

¹ *Ohio Geol. Surv.*, vii., p. 52

² *Missouri Geol. Surv.*, xi., 1897, p. 25.

³ *Geol. Surv. Georgia*, bull. 6a, 1898, p. 12.

⁴ *Wisconsin Geol. Surv.*, bull. 7, pt. 1, p. 14.

⁵ *W. Virginia Geol. Surv.*, iii., 1906, p. 70.

⁶ *Clays, Occurrence, Properties and Uses*, 2nd ed., 1914.

⁷ *Natural History of Clay*, 1912, p. 165.

most commonly met with in the course of geological investigations, and no attempt is made to widen its province by inclusion of many special and localized types extant. For these the reader is referred to one of the existing text-books devoted entirely to this subject.¹ Thus restricted, the argillaceous group may be said to comprise the following principal types:—

(A3. 1) Clay (p. 286).

(A3. 2) Fireclay (p. 290).

(A3. 3) Fullers Earth (p. 291).

(A3. 4) Æolian Clay (p. 292).

(A3. 5) Abyssal Clay (p. 294).

(A3. 6) Volcanic Clay (p. 295).

(A3. 7) Residual Clay (p. 297).

(A3. 8) Mudstone (p. 299).

(A3. 9) Shale (p. 300).

(A3. 1) **CLAY.**

[Fig. 90, Pl. xxvi.]

Lith. The distinguishing feature of true clay is its plasticity, due to adsorbed moisture by the extremely fine mineral particles of which it is composed. Expulsion of that moisture, whether by natural or artificial means, brings about a change of state, and the rock passes into a mudstone (A3. 8) or, with the development of lamination, into a shale (A3. 9). Beyond the feel of this rock, recognition of its plastic properties and colour, little is discernible from megascopic examination unless organic remains are present, which is a common feature. Colour, however, is significant. *White* implies absence of iron compounds, carbon or manganese, such clay being essentially composed of hydrous aluminous silicates. *Yellow* suggests incipient oxidation of iron compounds, more rarely chrome ochre. *Brown* clay shows evidence of ferric oxide passing into limonite. *Red* is chiefly due to the presence of ferric oxide (hæmatite) in finely divided state. *Mauve* colouring suggests manganese dioxide, limonite, and sometimes a trace of cobalt compounds. *Purple* is usually due to hydrated manganese dioxide with limonite. *Green* colour may be partly due to

¹ H. Ries, *op. cit.*

finely disseminated chloritic or glauconitic matter, in some cases to the presence of ferrous silicate and ferrous sulphate. *Grey* is inferential of the white type plus admixture of finely divided carbonaceous matter (graphite, carbonised wood, plant fibres, etc.). *Black* clay is usually due to an excess of carbonaceous matter, as above, or may be due to bituminous impregnation; in deoxygenated environments the black colour may be accounted for by amorphous ferrous sulphide, less commonly by black oxide of manganese. The significance of colour as inferential of sedimentary environment is discussed on page 449. Many examples exhibit blended colouring (variegation).¹ Clays with pebbles, flints, boulders, etc., are composite types, the products of particular conditions, *e.g.*, glacial boulder clay; in these instances the study of the large components and of the clay-matrix should proceed separately. Pyrite and calcite are frequently observed in these rocks.

Text. Exceedingly fine.

Shape. A to SA.

Min. Comp. *Al.* Quartz, orthoclase or soda-plagioclase feldspars, primary muscovite, biotite, ilmenite, epidote (in part), tourmaline, zircon, rutile, titanite; less commonly hornblende, garnet. Other accessory minerals are rare.

Au. Hydrous aluminous silicate, silica, hydroxide and carbonate of iron, muscovite, calcite, chlorite, epidote, glauconite, carbonaceous matter, secondary rutile and anatase. Of the hydrous aluminous silicates, the following have been specifically determined:² kaolinite, halloysite, micaceous halloysite, beidellite, montmorillonite; others in part determined, in part suspected, include:—allophane, pholerite or nacrite, rectorite, newtonite, cimolite, pyrophyllite, collyrite, schrötterite; in special types gibbsite, diaspore and bauxite occur. Many of these components must be primarily in a colloidal state.

Mech. Comp. Grade-size of the detrital particles is <0.01 mm. In many examples the diameters are considerably

¹ H. B. Milner, *Proc. Geol. Assoc.*, xxxvi., 1925, pp. 313-4.

² For chemical composition, consult Dana, *System of Mineralogy*; see also A. F. Hallimond, *Mem. Geol. Surv., Spec. Rep. Min. Resources, Gt. Britain*, xxix., 1925, p. 33.

less; below 0.005 mm., it is extremely difficult to promote deflocculation and secure isolation of particles. Below 0.002 mm. particles are practically in colloidal suspension. Ordinary microscopical observations impracticable on particles of diameters less than about 0.006 mm.

Micro. The difficulty of making a thorough microscopical study of clays from the petrological standpoint has already been emphasized. Much depends on the skill with which the section has been cut (of unconsolidated material): see p. 35. A certain amount of desiccation and loss of plasticity is bound to occur, which is an advantage. Much may be learnt of ordinary clays, however, if attention be paid to the following points. Study first the obvious detrital constituents revealed in the section; if these present difficulty on account of extreme fineness, segregate in the usual way for loose detrital sediments (p. 66). Quartz is usually in sub-angular flakes, seldom clear, but turbid with argillaceous matter; check with polarised light for holes in the slice which, at first glance, may be mistaken for large quartz fragments. Felspar, if present, is revealed by twin lamellæ in polarised light, *using high power objective*, incidentally essential in all work on clays. Mica is normally of the sericitic type and shows up in the form of silky wisps or flakes of characteristic birefringence and refractive index. Spherulitic siderite may occur in certain varieties. Iron-ores and carbonaceous specks are best displayed by employing strong incident light; this also is of great help in deciphering the authigenic matter or "clay paste" background in which the detrital particles are set. Polarised light will indicate approximately relative proportions of allogenic to authigenic matter, since quartz is nearly always the most prevalent detrital mineral, and is quickly revealed by characteristic interference (usually yellow colours in clay sections owing to the difficulty of producing them to standard thickness). The "clay paste" itself is normally observed to be structureless until high power magnification coupled with reflected light observations are made; these sometimes reveal a roughly organized development of crystal-line aggregates, often deeply coloured, almost opaque, and sprinkled with minute dust particles, probably iron-ores, carbonaceous specks, possibly rutile. Such aggre-

gates include one or more of the above-mentioned hydrous aluminous silicate minerals. They may be scaly, interdigitating plates of faint optical reaction; in other cases they suggest cleavage plates and are isotropic; other developments recall the characteristic habits of the micas, chlorites, etc. Patches of optically inert, indecipherable matter are common. When kaolinite does occur, it varies in form from tabular, pseudo-hexagonal plates to fan-like sheaves, vermiform or "rouleaux" assemblages of minute crystals.¹ Note refractive index and interference colours and compare with quartz. If the stage is rotated, using polarised light, kaolinite in thin section is observed to extinguish more tardily than quartz;² fibrous forms exhibit extinction angles from 15° to 20° ; basal cleavage flakes (common occurrence), if not too small, yield biaxial figure (p. 199). Much of the white, amorphous, powdery or "unglazed porcelain" looking material is probably halloysite, quite inert to polarised light. For description of other possible clay minerals, see p. 298.

Types. Fairlight Clays (Wealden), Fairlight, Sussex, variegated clays with spherulitic siderite, lignite and plant remains;^{3, 4} Gault (Upper Cretaceous), grey clay with glauconite, pyrite, and *foraminifera*; Reading Beds (Eocene), West Kent, Surrey, etc., mottled clays with plant remains; London Clay (Eocene), Harefield, Middlesex and elsewhere, bluish-grey clay with pyrite, selenite, calcite, etc.; Upper Oligocene lignitic, white and brown clays of Bovey Tracey, Devonshire; Pliocene, St. Agnes, Cornwall, brown clay with good detrital constituents; Glacial Boulder Clay (Cromer Till, etc.) of East Anglia, grey unstratified boulder clay with shell-fragments and pebbles of rocks of British and Scandinavian origin, etc.⁵

Ref. ¹ J. A. Howe, *Handbk. to Coll. Kaolin, etc.*, Mus. Pract. Geol., London, 1914, ch. vi., p. 145.

² R. E. Somers, *U.S.G.S.*, Bull. 708, 1922, p. 296.

³ H. B. Milner, *Proc. Geol. Assoc.*, xxxvi., 1925, pp. 312-15; also

⁴ E. Spencer, *Q.J.G.S.*, lxxxi., 1925, p. 667.

⁵ A. J. Jukes-Browne, *Stratigraphical Geology*, 1912, p. 627.

For further references to clay petrology, see under different types described.

(A3. 2) **FIRECLAY.**[†]

[Figs. 91, 92, Pl. xxvi.]

Lith. The typical Coal Measure fireclay of the Midlands is a highly siliceous clay, in some varieties coarse enough for quartz particles to give a "gritty" character to the rock; such approximate petrologically the siltstones A2. 7) or "greywackes" (A2. 6). Generally, however, fireclay is a very compact, homogeneous, consolidated clay-rock, with or without lamination. Colour varies from slate-grey to brown or brownish-black, some types possessing a mauve tint. Carbonaceous remains common, sometimes recognizable plant-fragments, more often just streaks of black material. Coarse varieties have the most detrital material, the finer varieties resembling shale in lithologic character and composition. Types with small silica content are often earthy.

Text. Exceedingly fine; sometimes "soapy"; earthy.

Shape. A to SA.

Min. Comp. Al. Quartz, felspar, muscovite, biotite, occasionally rock-particles, iron-ores and varied accessory minerals. Many examples yield plentiful "heavy" residues.

Au. Mica, chlorite, and minerals of predominantly micaceous habit (hydrous aluminous silicates), epidote, secondary silica and iron compounds, occasional calcite, and rutile ("clay-slate needles"). These constituents, some or all, form the "clay-paste" especially characteristic of these rocks, and difficult to analyse mineralogically.

Mech. Comp. Average grade 0.01 mm., but detrital quartz often of the silt grade, 0.05 mm. Clay-matter extremely difficult to break down into individual particles.

Micro. The chief feature of fireclay is the abundance of free quartz in the form of small, equi-dimensional grains of granular habit. In a few varieties these grains are so plentiful as to constitute the rock a siltstone in the strict petrological sense; generally, however, the dark brown matrix is very prominent. Felspar

† Commercial fireclay includes a number of differently formed clays and allied rocks suited to various refractory purposes. The term is here restricted to highly siliceous, transported clays of the Coal Measure type, distinct from miscellaneous residual clays, which receive separate consideration in accordance with their undoubted difference in origin and constitution.

is occasionally diagnosed, but more often is probably represented by decomposition products. The paste includes minute scales of secondary mica, iron-ore dust (probably ilmenite), and obvious rutile needles. This form of rutile differs considerably from the primary detrital type; it occurs in slender, acicular crystals, often of perfect formation, almost colourless and with extremely high refractive index; twin forms also observed; Teall records needles of rutile of this type 0.001 mm. in thickness, averaging 0.002 mm., their length being from 8 to 30 times their breadth.¹ Usually where lamination is developed, there is a certain degree of parallelism in the orientation of the detrital elements in the matrix, also discernible in the fibrous minerals of the latter. Where no bedding occurs, the larger grains are distributed haphazardly through the "paste" and the rock is practically devoid of any distinctive micro-structure.

Types. Coal Measure fireclays of Newcastle, etc., Northumberland, coarse and fine laminated varieties;² Middle Coal Measure fireclays of Stockingford, Nuneaton, Warwickshire; Coal Measure clays of Leeds, Halifax and Huddersfield, Yorkshire, typical siliceous clays with carbonaceous matter, micaceous minerals, rutile and other accessories; Millstone Grit, Glenboig Fire-clay, Central Valley, Scotland.^{3, 4}

Ref. ¹ J. J. H. Teall, *Mineralogical Mag.*, vii., 1887, p. 201.

² W. M. Hutchings, *Geol. Mag.*, 1890, pp. 264, 316; 1891, pp. 164, 304; 1894, pp. 34, 64; 1896, pp. 309, 346.

³ J. W. Gregory, *Proc. Roy. Soc. Edinburgh*, xxx. 1910, p. 348.

⁴ J. S. Flett, *Geology of Glasgow District, Mem. Geol. Surv.*, 1911, p. 219.

See also *Mem. Geol. Surv., Refractory Materials*, xxviii., 1924, p. 3.

(A3. 3) FULLERS EARTH.

[Fig. 93, Pl. xxvi.]

Lith. A soft, earthy rock, of distinctive texture, colour and physical properties. Bedding may or may not be developed. Colour greenish-brown, grey, bluish-grey or yellow. Possesses marked absorbent properties. When scratched with the finger-nail, yields a polished streak. Adheres to the tongue. Crumbles in water and cannot be "muddled."

Text. Very fine, close-grained, powdery or earthy; distinct "clayey" feel.

Shape. SA.

Min. Comp. *Al.* Quartz, mica, calcite; accessory minerals include iron-ores, zircon, apatite, locally barite, sphalerite, titanite, galena, hornblende, biotite.²

Au. Hydrated silicate of alumina, which makes up the bulk of the rock; originally thought to be some form of soda-lime felspar, but more probably one or more of the clay minerals (p. 287); montmorillonite has been recognized in some examples; also limonite, mica and pyrite.

Mech. Comp. Average grade-size < 0.005 mm.

Micro. Very difficult to study in section. Usually an abundant and distinctive mineral suite can be separated in the ordinary way. Plant remains and micro-organisms often observed. Practically structureless; essentially an aggregate of granular aluminous silicate particles plus varying amount of detrital constituents.

Types. Fullers Earth Rock (Bathonian), W. of England;¹ Fullers Earth (Lower Cretaceous), Redhill, Nutfield, etc., Surrey, with interesting accessory mineral assemblage.²

Ref. ¹ A. J. Jukes-Browne, *Stratigraphical Geology*, 1912, pp. 415, 422, 424, 425.

² G. M. Davies, *Proc. Croydon Nat. Hist. Soc.*, 1915-16, pp. 63, 92, 93.

(A₃. 4) **ÆOLIAN CLAY.**

[Fig. 94

This subdivision is exemplified by the Eurasian Loess and American Adobe, both partly of æolian and partly of fluvio-glacial origin.

Lith. Yellow, buff, grey or brown calcareous clay, often somewhat silty. Very slightly coherent, and easily powdered in the fingers, yet possessing remarkably resistant properties to subærial erosion. Plant remains in various stages of preservation scattered throughout the rock.

Text. Very fine, compact, earthy.

Shape. A.

Min. Comp. *Al.* Quartz, orthoclase, plagioclase, muscovite, biotite, magnetite, amphibole, pyroxene, etc.

Au. Calcite, dolomite, silica, clay material, carbonaceous matter,

Mech. Comp. Average grade <0.0025 mm. "Out of 150,000 particles examined under the microscope only about 3% measure above .0025 of a millimetre and 1% over .005 of a millimetre" (loess);¹ with adobe the upper limit is about 0.08 mm.

Micro. The constituent particles of this type of deposit are normally very fresh and transparent; their unassorted size and markedly angular shapes are characteristic. When cohesive, the calcareous nature of the cementing medium is seldom in doubt. Vegetable remains prevalent. Practically no organized micro-structure. Microscopical examination confirms the entirely haphazard nature of these deposits.



FIG. 94. Grains from the Loess, China. (After Merrill.)
[x 25.]

Types. Loess of China,² Russia, Germany (Rhine Valley), etc.; similar deposits of the Mississippi Valley, U.S.A.;³ adobe of South California, Colorado, Wyoming, etc.⁴

Ref. ¹ G. P. Merrill, *Rocks, Rock-Weathering and Soils*, 1913, pp. 315-322; also E. V. Emerson, *Journ. Geol.*, xxvi., 1918, pp. 532-541.

² F. von Richthofen, *China*, vol. i., 1877; also R. Pumpelly, *Amer. Journ. Sci.*, xvii., 1879, p. 133.

³ C. R. Keyes, *Amer. Journ. Sci.*, vi., 1898, p. 299.

⁴ I. C. Russell, *Geol. Mag.*, 1889, pp. 242-259, 289-295.

(A3. 5) **ABYSSAL CLAY.**

Lith. This subdivision includes varied muds and clays laid down at the greatest depths of the oceans. These rocks are in general very finely divided, and are studied as aggregates of incoherent particles from samples dredged from sea-bottom. In certain cases a latent degree of coherency causes ready solidification to mud-stone (*q.v.*) on exposure to the atmosphere. Varieties are chiefly distinguished by colour, though there are striking differences in mineral composition revealed by microscopic observations. *Red Mud* owes its colour to ferric oxide. *Red Clay* (so-called) varies from yellowish-red to purple, depending on the ferric oxide and manganese peroxide contents. *Blue* and *Grey Muds* are coloured chiefly by ferrous sulphide plus organic matter, the latter especially characteristic of *Black Muds*; *Green Mud* is largely due to the presence of glauconite.

Text. Extremely fine, soft, often greasy.

Shape. A.

Min. Comp. *Al.* Quartz, iron-ores, tourmaline, zircon, garnet; where volcanic rocks have contributed, augite, olivine, hypersthene, hornblende, plagioclase, sanidine, etc.

Au. Silica, calcite, glauconite, lime phosphate, argillaceous matter.

Mech. Comp. Variable, down to 0.005 mm., but may contain particles of much larger size; some of the "muds" average 0.12 mm.

Micro. Usually a sharp contrast is shown between the organic and inorganic ingredients of these deposits. In the *Red Muds*, quartz and the common terrigenous minerals (above) are associated with diatom frustules, sponge spicules and rarely radiolarian tests. *Red Clay* contains (in order of abundance) magnetite, manganese, felspar, glassy volcanic particles, augite, pumice, hornblende, pelagonite, quartz, plagioclase, mica, phillipsite or zeolitic matter, cosmic spherules, sanidine, scoriæ, glauconite, olivine, lapilli, rock-fragments, zircon, tourmaline, epidote, garnet. Organic remains include shark teeth, diatoms, *radiolaria*, *foraminifera*, etc. *Blue* and *Grey Muds* show quartz, orthoclase, plagioclase, green hornblende, augite, white and black mica, epidote, chlorite scales, zircon, tourmaline, and miscellaneous rock-fragments; glau-

conite not common. Abundant siliceous and calcareous micro-organisms. The *Black Muds* show variable mineral composition, much quartz, carbonaceous matter, mica, etc., with pyrite as a conspicuous constituent; organic remains include planktonic diatoms and pelecypod fragments. *Green Mud* is distinguished by its glauconite, also by some doubtful substance of organic origin. Minerals include quartz, felspar, magnetite, hornblende, augite, tourmaline, zircon, garnet. In all these deposits, a contribution from submarine volcanic rocks or far-travelled volcanic dust—the product of violent eruption—determines the presence of ordinarily uncommon sedimentary rock minerals.

Types. Deep Sea deposits of the Challenger Expedition, Atlantic, Pacific, etc.¹

Ref. ¹ J. Murray & A. F. Renard, *Deep Sea Deposits, Challenger Report*, 1891; also L. W. Collet, *Les Depots Marins*, 1908.

(A3. 6) VOLCANIC CLAY.

Under this heading are placed certain distinctive clays of definite constitution and origin, e.g., *Bentonite*, implying derivation from devitrified and chemically altered glassy, volcanic ash or tuff. The chief types have been described from America. Closely allied is the abyssal variety of volcanic mud (q.v., above).

Lith. Extremely variable in external appearance and superficial properties. Generally well stratified. Colour white, cream, dull green, sometimes blue or pink. Yellow to brown on weathering. Readily absorbs moisture, becoming plastic; excess of water causes formation of slime. Some samples exhibit sandy streaks or patches. Organic remains rare.

Text. Compact, soft; “some have a very loose felt-like texture.”¹

Shape. A to SA.

Min. Comp. Al. Quartz, felspar, mica, ferromagnesian minerals, zircon, apatite, iron-ores.

Au. Montmorillonite, less commonly beidellite (in bentonite); non-bentonitic clays of similar origin may include micaceous halloysite, halloysite and kaolinite. Abyssal volcanic mud is characterized by siliceous and calcareous matter.

¹ See Ref. ¹, p. 296.

Mech. Comp. Average grade 0.01 mm., but much of the material is of colloidal dimensions.

Micro. In the case of bentonite "microscopic examination between crossed nicols . . . shows that the characteristic mineral of bentonite is crystalline. . . . In some specimens the material is very fine grained, but in most of them the crystal grains can be seen even with low power magnifications. The mineral has a micaceous habit, and moderately high birefringence perpendicular to the cleavage. The groups of plates that have been derived from a single glass fragment commonly have a definite arrangement, and sharply outline the original fragment. In most types of bentonite the crystal plates stand perpendicular to the original surface of the glass fragment, and the resulting crystalline area is now composed of two parallel rows of micaceous plates that often have a parting line between them. In other specimens the micaceous plates have developed parallel to the sides of the glass."¹ Generally the main constituent of these volcanic clays is some form of glass, the particles being essentially sections of "bubble boundaries." Detrital quartz tends to be restricted; feldspars and above-mentioned accessory minerals prevalent. These rocks vary in mineral composition, but all present interesting problems in microscopical analysis; the latter may be considerably aided by employing $\frac{1}{12}$ " oil-immersion objective.

Types. Bentonite, Big Horn Basin, Wyoming, with andesine, orthoclase, biotite and accessory minerals, hydrous aluminous silicates (as above);² also examples from Kansas, Texas, Oklahoma, etc., etc.;¹ volcanic mud from deep sea deposits (Challenger Expedition);³ bentonite, Alberta, Canada, associated with coal, etc.⁴

Ref. ¹ C. S. Ross & E. V. Shannon, *Journ. Amer. Ceramic Soc.*, ix., 1926, pp. 77-96.

² D. F. Hewett, *Journ. Wash. Acad. Sci.*, vii., 1917, pp. 196-198.

³ J. Murray & A. F. Renard, *Deep Sea Deposits, Challenger Report*, 1891.

⁴ R. L. Rutherford, quoted by W. H. Twenhofel, *Treatise on Sedimentation*, 1926, p. 208. (Further references to this type of clay are given at the foot of pp. 204-208 of the "Treatise.")

(A₃. 1) RESIDUAL CLAY.

Lith. Residual clay, as the name implies, is any clay-material formed *in situ* from the decomposition of some particular rock whose minerals, by various destabilisation processes, determine the nature of the ultimate clay-substance; in this respect, residual clay differs fundamentally from transported clay. The normal feature of residual clay is the extremely finely divided state of the clay-substance, though often the presence of fragments of miscellaneous rocks and minerals, more resistant to weathering than the parent-substances of the clay, determine an unsorted character. Some degree of plasticity is usually apparent, but with expulsion of moisture, the clay hardens rapidly. Bedding normally absent, but a crude lamination of the solidified material is sometimes apparent. Organic matter not common, but where it occurs is mainly due to plant remains in varied stages of carbonisation. Many residual clays are colourless or only slightly tinged with iron oxide staining; examples are the so-called "*Pocket Clay*," formed in solution-cavities or pipes in limestone deposits, *Bauxite*, *China Clay* and *China Clay Rock*. The more intensely coloured varieties are illustrated by *Laterite*, an exceedingly controversial substance, which is reddish-brown or yellow.

Text. Exceedingly fine and uniform as far as the clay-substance is concerned; where rock-fragments or "sand" are present, the texture becomes gritty, sometimes even coarse; laterite is variable, some examples being coarse, earthy and friable.

Shape. Clay particles A, less commonly SA. Most embedded rock-fragments are angular, like the components of a breccia. Loose quartz often corroded, therefore rounded.

Min. Comp. Rock-fragments may be of igneous or sedimentary origin; in "pocket clay" they are less common, but include limestone, dolomite, occasionally basic igneous rocks; bauxite is, on the whole, remarkably free from large constituents, though fragments of basalt have been noted in one case; china clay and china stone (china clay rock) often include quartz-tourmaline rock (schorl), pegmatite, altered granite, cassiterite; laterite may comprise fragments of mother-rock, *e.g.*, lava, basalt, granite, gneiss, also sandstone. The finer mineral components are quartz, hæmatite, limonite,

and varied accessory minerals; in china clay a distinctive assemblage of quartz, tourmaline, topaz, mica, cassiterite, fluorite, is characteristic. The clay-substance varies considerably; in pocket clay it is predominantly hydrated aluminous silicate, with kaolinite, halloysite, possibly montmorillonite, etc.; in bauxite it is essentially alumina and some form of ferric hydrate (? gothite or limonite), as is the case with laterite; the alumina may be represented either by gibbsite or diaspora, though often the clay-substance gives the impression of being an amorphous mixture rather than an individualized species.

Mech. Comp. Clay-material extremely fine, often colloidal. Gritty constituents usually conform to the medium sand-grade.

Micro. The "floating" minerals or rock-fragments are the first components to attract attention, and seldom present great difficulty in diagnosis. It is usual to find quite an arbitrary distribution of these constituents in the clay-mass, no particular relationship between the two being apparent. The clay-substance may or may not present a certain degree of micro-structure; in pocket clay it is reduced to a minimum unless much crystalline kaolinite is present, when the interlocking scaly plates of that mineral are discernible. Bauxite is frequently quite without structure, though in some examples a fibrous character (? gibbsite) with enveloping brown material (ferric oxide or hydrate) is conspicuous. In china clay, colourless, pseudo-hexagonal, scaly plates of kaolinite are associated with corroded quartz, white mica, topaz, etc., often in the form of interlocking crystal-masses set promiscuously in a very fine kaolinitic cement; the latter may include material having the properties of halloysite. Laterite presents considerable variation in micro-structure. Scales and fibres due to gibbsite may be observed, these often picked out by ferric hydrate staining; intimately mixed with this material are quartz particles, iron-ores, carbonaceous matter, etc. Diaspora has been recorded from some varieties of laterite, which in many respects closely resembles bauxite in micro-structure.

Types. Pocket Clay from the Carboniferous Limestone of Derbyshire, Staffordshire, etc.; Bauxite deposits of Antrim;¹ China Clay of West Cornwall;^{2, 3, 4} Laterite of India,⁵ Seychelle Islands,⁶ French Guinea,⁷ etc.

Ref. ¹ *The Intra-basaltic Rocks of N.E. Ireland*, Mem. Geol. Surv., Ireland, 1912.

² A. Howe, *Handbook to the Collection of Kaolin*, Mus. Pract. Geol., 1914, pp. 145-158.

³ *Mem. Geol. Surv.*, 347, 1909, ch. ix.

⁴ J. W. Gregory, *Elements of Economic Geology*, 1928, ch. xiii.

⁵ T. H. Holland, *Geol. Mag.*, 1903, pp. 59-69 & refs. cited.

⁶ M. Bauer, *Beitrage zur Geol. der Setchellen*, *Neues Jahr. für Min., etc.*, 1898, ii., p. 163.

⁷ L. L. Fermor, *Geol. Mag.*, 1915, pp. 28, 77, 123. General Reference.

T. V. M. Rao, *A Study of Bauxite*. *Mineralogical Mag.*, xxi., 1928, pp. 407-430.

(A3. 8) **MUDSTONE.**

[Fig. 95, Pl. xxvi.]

Lith. Consolidation of clay without the production of fissile characters results in a type of rock to which, for want of a better name, the term "mudstone" is applied; "clay stone" would suit equally well. Chief lithological characters are colour, as variable as in clays, though usually dark green, brown or grey or a blend of these, and an absence of anything but the crudest lamination. Organic remains, especially carbonaceous, very common. Oblique jointing and limonitic staining on planes thus developed are frequent features.

Text. Very fine; smooth surfaces.

Shape. A to SA.

Min. Comp. As for clay (*q.v.*, p. 286).

Mech. Comp. Average particle dimensions <0.01 mm.

Much of the material is in a very fine state of division and is ultra-microscopic. (See relevant remarks under Clay, p. 288).

Micro. Although this rock-type lacks lamination, some degree of parallelism of orientation of constituent minerals is often discernible under the microscope, the result of compaction. Detrital matter together with organic remains are set in a fine clay-matrix in which certain components, *e.g.*, silica, calcite, limonite, carbonaceous matter and one or more hydrated aluminous silicates, can be recognized. The rock is sometimes traversed by veins of secondary silica or calcite carrying pyrite and related iron or copper ores. In certain

types white mica, chlorite and secondary rutile are produced as a result of induration, such constituents forming a felted mass wrapping round quartz and the larger components.

Types. Graptolitic mudstones, Ordovician and Silurian, Welsh Borders; Liassic mudstones (calcareous, pyrite and carbonaceous matter), Bridport, Dorset; Wealden, Weald Clay mudstones, Sussex, Kent, etc.

General References. J. J. H. Teall, *Mineralogical Mag.*, vii., 1887, pp. 201-204 (for rutile needles, etc.); G. W. Tyrrell, *Principles of Petrology*, 1926, p. 214.

(A3. 9) **SHALE.**

[Fig. 96, Pl. xxvi.]

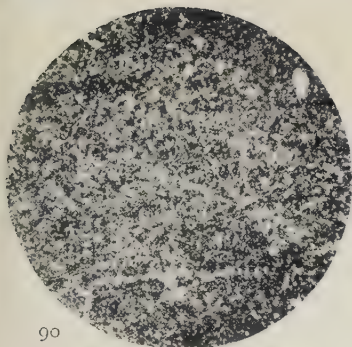
Lith. Shale differs fundamentally from mudstone in its possession of definite laminations or bedding planes, parallel to which it splits with comparative ease. It represents, in fact, one stage further in consolidation of clay, mud, etc., than the mudstone. Lamination may be thin or thick and is accordingly significant. Many fluviatile or lacustrine shales exhibit remarkably thin laminæ, for instance, varve shales. Colour, as with clays (*q.v.*, p. 286), frequently suggests conditions of deposition; grey, black or blue shales are usually derived from muds of marine, estuarine or fluviatile origin initially rich in carbonaceous and sulphide materials; these are the commonest types. Red shale owes its colour mainly to ferric oxide; green shale chiefly to chloritic material resulting from ferromagnesian mineral decomposition. Organic remains, both animal and vegetable, very prevalent; there is often an inherent relationship between nature and quantity of organisms and the colour of the shale: see ref. 1, p. 302. Lignite seams and secondary pyrite common, especially in estuarine and fresh water types; mineralized veins, *e.g.*, calcite, quartz, barite, often developed; prominent jointing observed at right angles or obliquely to the laminæ, or both.

Text. Fine, smooth; with inclusion of sand becomes gritty.

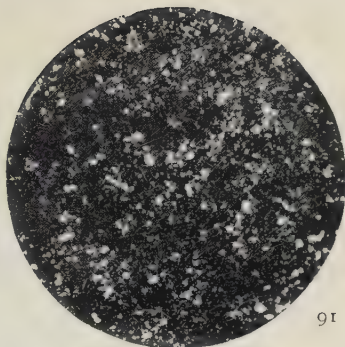
Shape. A to SA.

Min. Comp. *Al.* Quartz, mica, iron-ores and varied accessory minerals; occasionally feldspar.

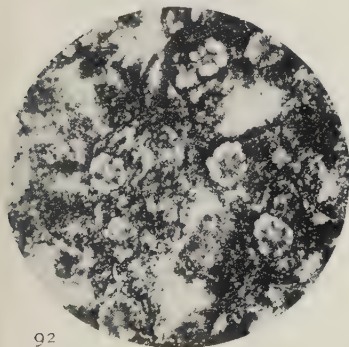
Au. Secondary silica, calcite, limonite; usually abundant chloritic matter, amorphous carbon, rutile needles; less commonly titanite, leucoxene. Much of the "background" of these rocks is indecipherable



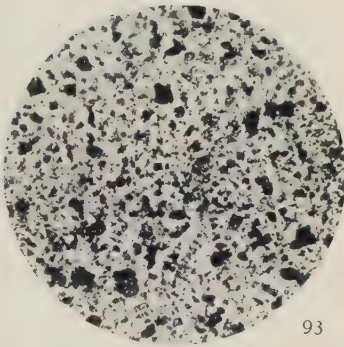
90



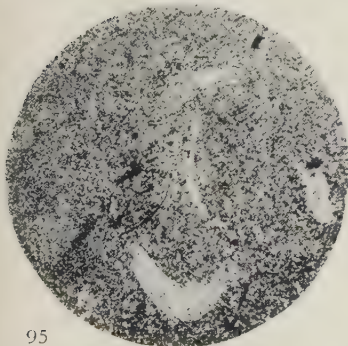
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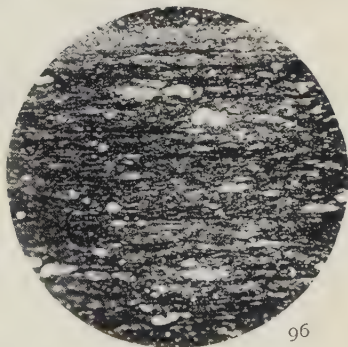
92



93



95



96

CLAY, MUDSTONE AND SHALE.

- FIG. 90. London Clay (Eocene), Herne Bay, Kent. [x 20.]
 „ 91. Fireclay (Coal Measures), Stockingford, Nuneaton. [x 25.]
 „ 92. Fireclay (Coal Measures), Staffordshire, with spherulitic siderite. [x 13.]
 „ 93. Fullers Earth (Aptian), Surrey. [x 45.]
 „ 95. Mudstone (Up. Lias), West Bay, Dorset. [x 25.]
 „ 96. Monterey Shale (Miocene), Los Angeles, Calif., U.S.A. [x 18.]

and represents products of induration of aluminous silicates mentioned in connexion with clays.

Mech. Comp. Detrital particles vary from silt to clay grade, usually, however, conforming to the former limits, 0.1 mm.-0.01 mm.; the finer particles are of true clay dimensions, frequently unmeasurable by ordinary means.

Micro. The dominant character of shale is the parallel orientation of its constituents, both organic and inorganic, revealed by thin section; such parallelism is best observed in sections cut transverse to the bedding, but the study should always be supplemented by a section cut parallel to the bedding. The latter shows the mutual relationship of the constituents as they lie along one bedding-plane of the rock; in the case of organisms, *e.g.*, plant spores, this amounts to a horizontal section; the relative proportion of detritus to shale-substance is also conspicuous in such horizontal sections. Transverse sections reveal the nature of the bedding, slight changes in constitution of material with alternating laminæ, and longitudinal or cross-sections both of minerals and organisms. Products of infiltrating solutions deposited along bedding-planes, in veins or cracks at right angles or obliquely to these, are also readily studied by such transverse sections. Usually the contrast between parallel and transverse sections is very marked. Shale-substance may be difficult to decipher, but the titanium minerals are normally conspicuous; much of the brown, translucent matter in many varieties is of carbonaceous origin and is frequently optically inert. Investigation by reflected light is often helpful, when limonite, aluminous silicate, secondary silica, green chloritic material, etc., may be clearly picked out in the mass. Muscovite, the ubiquitous shale mineral, presents characteristic features and is seldom difficult to diagnose. Accessory minerals must be studied from pulverized rock.

Types. Stockdale Shales (Silurian) of the Lake District, different coloured shales and their palæontological significance;¹ Upper Carboniferous shales, South Wales, with abundant rutile, etc.;² Culm Shale, N. Cornwall, with a silty form of carbon, etc.;³ Lias shale, Dorset, Yorkshire, etc., with abundant organic remains, calcite, pyrite, jet; Kimmeridge Shale, Dorset: excellent example for study by horizontal and transverse

sections; Wadhurst Clay (shale developments) for ostracods, lignite and secondary minerals.

Ref. ¹ J. E. Marr, *Q.J.G.S.*, lxxxi., 1925, p. 113.

² W. M. Hutchings, *Geol. Mag.*, 1896, p. 310.

³ C. A. McMahon, *Geol. Mag.*, 1890, p. 108.

General Reference.

A. Brammall, *Mineralogical Mag.*, xix., 1921, p. 211.

(AB) **CALCAREO-ARGILLACEOUS ROCKS.** Transitional sediments partaking of certain prominent characteristics common both to argillaceous and calcareous rocks are sufficiently distinctive and widespread in development to warrant separate notice here. These are exemplified by the marls and calcareous shales. According to the scheme adopted they may be designated conveniently as follows:—

(AB. 1) Marl (p. 302).

(AB. 2) Calcareous Shale (p. 303).

(AB. 1) **MARL.**

[Fig. 111, Pl. xxix.

Lith. The term marl is somewhat loosely applied to material having most of the normal attributes of clay, but also exhibiting considerable amounts of lime and, or magnesium carbonate. Usually a light coloured rock is implied, but this is not invariable, red, purple, chocolate and brown types occurring. Marls are usually homogeneous in superficial characters, often possessing plastic properties; with induration they pass into marlstone (calcareous mudstone), calcareous shale and argillaceous limestone, sometimes known as "cement-stone" (p. 311). True marl, like clay, lacks obvious bedding and seldom exhibits any striking external structures, save those dependent on the presence of organic remains. Rudaceous constituents, pebbles, boulders, etc., may occur on a large scale. Some examples are gritty.

Text. Normally very fine, homogeneous, compact; plastic, "soapy."

Shape. A to SA.

Min. Comp. *Al.* As for clay (*q.v.*, p. 287).

Au. As for clay, but with appreciable amount of calcareous matter disseminated in the clay-matrix;

chemical analyses often show presence of magnesia, indicating magnesium carbonate. Anhydrite, gypsum, barite, celestite, are locally prevalent. Glauconite common in marine types.

Micro. Under the microscope marls present much the same features as clays; the detrital constituents are scattered haphazardly through a matrix in which much of the material is difficult, if not impossible, of diagnosis in terms of known minerals. Calcareous matter is generally betrayed by "twinkling" on rotating the polariser alone. Sulphates, if present, are often finely crystallized in fibrous aggregates of patchy occurrence. In coloured varieties the pigment is observed either as a staining material for the bulk of the rock, or as irregular streaks traversing it. Where glauconite is in evidence, it frequently exhibits organic structure, *e.g.*, *foraminifera*, and gives a distinctive appearance and colour to the rock. For the rest, the main mass of the rock is structureless unless the component minerals of the matrix can be made out, when a mosaic of equi-dimensional particles, often interrupted by dense interstitial matter, may be observed.

Types. Keuper Marls of Leicestershire, different coloured marls with gypsum, etc.;¹ Chalk Marl of England, with glauconite, etc., and "Chloritic Marl," Dorset, Isle of Wight, etc.;² Oligocene (Bembridge) marls, Isle of Wight, white, red and blue marls with calcareous concretions and freshwater shells.³

Ref. ¹ T. O. Bosworth, *Keuper Marls around Charnwood*, Leicester, *Leicester Lit. & Phil. Soc.*

² W. Hill, *Cretaceous Rocks of Britain*, *Mem. Geol. Surv.*, ii., 1903, ch. xxii.

³ J. W. Judd, *Q.J.G.S.*, xxxvi., 1880, p. 169, and E. Keeping, *Geol. Mag.*, 1887, p. 48.

(AB. 2) CALCAREOUS SHALE.

Lith. Shale in which occurs an appreciable quantity of lime is designated as calcareous shale, though no particular quantity has ever been specified; the term consequently has a wide and varied interpretation. It should be confined to indurated marl in which definite laminæ have been produced as a result of compaction, a stage further in consolidation of marlstone. Argillaceous matter, however, is always in excess of calcareous in these rocks. Superficially there may be little to

differentiate calcareous from ordinary shale, though the former is usually rather paler in colour than the latter, commonly grey, yellow, brownish-white. Lamination is often extremely fine; where the calcareous matter is concentrated in some layers more than others, alternating light and dark colour-banding may be manifest. Organic remains common.

Text. Very fine.

Shape. SA.

Min. Comp. AL. As for Shale (*q.v.*, p. 300).

Au. Calcareous matter in addition to the normal shale minerals (p. 300), but often with much less rutile and limonite; silica is usually abundant and amorphous carbonaceous matter prevalent in dark coloured types.

Mech. Comp. The bulk of the material composing these rocks is very fine indeed, <0.005 mm., the tendency to extremely fine particle dimensions increasing with amount of lime.

Micro. The presence of calcite in these rocks is revealed by the ordinary "twinkling" with the polariser alone. In some instances, however, chemical analysis may show the presence of lime in excess of that necessary to satisfy specific minerals, and which might be anticipated in the form of a calcareous cement, yet no optical reaction can be discerned. As the rock passes more into the true limestone, calcite *per se* becomes prominent; argillaceous matter diminishes and the hybrid type "argillaceous limestone" (*q.v.*, p. 311) is produced; this tends to exhibit certain characteristic microscopic features differentiating it from the type here under consideration. The study of calcareous shales should proceed as with ordinary shales, two sections being desirable, one parallel and one transverse to the laminae. If reaction for calcite is positive, note particularly the strength and nature of development of this material, what relationship it bears to included organisms (if any), to detrital quartz, and to associated authigenic matter.

Types. Silurian (Woolhope) calcareous shale, Shropshire (Coalbrookdale, etc.);¹ Devonian Calceola Shales, South Devon;² Lias, Bridport, Dorset, calcareous shale in which the cementing matter can be well studied; Oxfordian, Weymouth, Dorset, with free calcite, pyrite, plant remains and fine laminations; Lower and Middle Purbeck, Dorset, calcareous shales with abundant

organic remains, very fine laminæ, plant remains; Wadhurst Clay (Wealden) shales, with lignite, pyrite, fine laminæ and colour-banding.

Ref. ¹ A. J. Jukes-Browne, *Stratigraphical Geology*, 1912, p. 165.

² W. A. E. Ussher, *Q.J.G.S.*, xlv., 1890, p. 499.

(B) ORGANIC ORIGIN. In this category are placed all those sediments owing their origin essentially to the accumulation of organic matter of diversified nature. In contrast to rocks of mechanical origin which, as now explained, imply transport of constituents in a majority of cases, rocks of organic origin are for the most part formed *in situ*; they represent accumulations of the harder parts or more stable components of both animal and vegetable matter in environments and under conditions differing considerably from those normal to detrital sediments. These fundamental differences of origin are amply reflected by the rocks themselves, both in composition and micro-structure. The purest types are composed entirely of organic matter, but such are comparatively scarce in nature; usually a small but appreciable amount of mechanically-born sediment is apparent to emphasize the influence, even at a distance, of terrigenous material; with increase in proportion of detrital constituents, less pure types are evolved, and gradually the gap is bridged between the two primary divisions (A and B). Further, these organically-formed rocks are inherently susceptible to alteration both during and subsequent to consolidation by chemical reactions, set up as a result of access of various substances in solution. Such changes are, when widespread and comprehensive, productive of types closely related to sediments fundamentally of inorganic chemical origin (C).

The intensive petrographic study of these rocks implies a working knowledge of the essentials of palæontology and, to a lesser extent, of palæobotany, since three main features come under observation in all cases: the organic remains, the matrix or cement (which may be of biochemical or simply of inorganic origin), and the inherent structure, *i.e.*, relationship of organic constituents to matrix. To this must be added in appropriate instances, the determination of foreign, mostly detrital, occasionally submarine volcanic or other igneous, matter. Where marked changes in chemical composition are involved (metasomatism), a knowledge of the common interactions between the simpler mineral compounds, helps considerably in the interpretation of the phenomena displayed.

For present purposes, rocks in this category may be subdivided into five main groups on the basis of fundamental biochemical composition :—

- (B1) CALCAREOUS (p. 306).
- (B2) SILICEOUS (p. 319).
- (B3) FERRUGINOUS (p. 325).
- (B4) CARBONACEOUS (p. 326).
- (B5) PHOSPHATIC (p. 341).

(B1). CALCAREOUS DEPOSITS. These comprise the limestones, built up by the accumulation of varied fossil (or recent) shell-fragments, corals, micro-organisms, etc., set in a matrix partly of organic, partly of inorganic origin. Distinctive types are determined either by characteristic fossils, by peculiar structures, or by the presence of particular compounds or impurities. Some degree of consolidation is common to all except the abyssal oozes conveniently considered here. Thus we may recognize :—

- (BI. 1) Limestone (including distinctive fossil types (p. 307)).
- (BI. 2) Dolomitic Limestone (p. 312).
- (BI. 3) Oolitic and Pisolitic Limestone (p. 314).
- (BI. 4) Abyssal Ooze (p. 316).
- (BI. 5) Chalk (p. 317).

(BI. 1) **LIMESTONE.**

[Figs. 97-102, Pl. xxvii.]

Lith. Extremely variable, depending primarily on the nature and quantity of fossil fragments present, on their degree of preservation and cementation; also on the purity of the rock as determined by foreign matter or secondary constituents developed. Every gradation from the fine, compact, close-grained type, void of recognizable organisms, to the coarse shelly limestone, occurs. Where organic remains are scanty or wanting and the cement predominates, coarse to fine crystalline characters may be observed. In some examples composed of mutually interferent calcite crystals of megascopic size and uniformity of dimensions, the "sugary" or "saccharoidal" character is apparent. Contrasted are those types in which the rock is made up of a homogeneous aggregate of microcrystalline calcite particles (etc.), with difficulty distinguishable lithologically from certain compact grits or quartzites. In doubtful cases the acid test should always be applied: with normal limestone effervescence when cold is marked.

Colour is a rough guide to purity; white, cream-coloured, yellow and pale grey rocks are normally the most free from detrital and other contamination; red limestone implies disseminated oxide of iron; brown to chocolate-brown developments are mainly produced by strong impregnation of limonite; dark grey to black types depend largely on finely disseminated carbonaceous matter; greyish-brown or ochreous rocks often imply the presence of considerable argillaceous matter. Appreciable amounts of detrital quartz result in gritty or sandy limestone; when excessive, the rock passes into calcareous sandstone or grit (p. 276). Bedding normally developed, but may not be apparent in hand-speci-

men; more commonly observed in the finer, non-shelly types. Limestones are frequently the host of metalliferous and other minerals which may, in certain cases, be conspicuous; mineral veins, *e.g.*, silica, calcite, etc., are often observed traversing the rock in all directions. Prominent structures determined by oolitic or pisolitic developments are separately noticed (Bl. 3, p. 314).

The following are among the common organic contributors to these rocks, whose remains are often determinable megascopically:—*brachiopoda*, *actinozoa* (corals), *crustacea* (in particular the *ostracoda*), *echinoderma* (including the *crinoidea*), *foraminifera* (in part), *mollusca* (lamellibranchs and gasteropods). *Algæ*, *foraminifera*, *polyzoa* or *bryozoa*, and more rarely *pteropoda*, are among the well-known micro-organic contributors to these rocks.

Text. Highly variable, entirely dependent on presence (or absence) and size of organic remains, also on the degree of compaction of the cementing material. The average type is probably of medium texture; many unfossiliferous limestones are very close-grained, particles averaging 0.1 mm.-0.2 mm., and are thus fine-textured rocks.

Shape. Organic fragments tend to preserve something of their essential morphology, though brittle shells may be disintegrated into several highly angular parts by compaction of the rock. Crystalline cementing material exerts its inherent tendency to produce natural shape, though this may be prevented where there is excess of material. Detrital particles usually exhibit considerable rounding.

Min. Comp. Al. When detrital matter occurs, it usually consists of quartz, iron-ores (chiefly ilmenite), tourmaline, zircon and garnet, *i.e.*, the stable accessory minerals. In a few instances the detrital suite may be considerably enriched, *e.g.*, contribution of material from submarine volcanic rocks, etc. Shallow-water limestones contain most allogenic minerals.

Au. Calcareous mud, either in the form of finely divided amorphous material or as crystalline calcite: the latter may represent a product of recrystallization. Silica is sometimes chalcedonic, often cryptocrystalline, or may occur as secondary quartz. Limonite, hæmatite, carbonaceous matter and/or argillaceous material common. With advent of magnesium car-

bonate, the rock passes into a dolomitic limestone, type BI. 2 (q.v., p. 312).

Organic Material. This may imply the presence of calcite, aragonite, less commonly of silica. Calcareous *algæ* are composed either of calcite or aragonite; similarly the corals (*actinozoa*) and *polyzoa*. Crustacean tests are mainly calcite, chitinous material, less commonly phosphate of lime; *brachiopoda* and *echinoderma* are of calcite, similarly the vitreous forms of *foraminifera*; the porcellaneous forms of the latter are probably of aragonite in most cases. *Lamellibranchia* vary, certain genera (e.g., *Trigonia*, *Pinna*, *Spondylus*, *Unio*, etc.) exhibiting an inner shell-layer of aragonite, the outer being of calcite; *Ostrea*, *Pecten*, etc., are entirely of calcite, otherwise many forms are composed of aragonite. *Gasteropoda* are mainly of aragonite; a few combine both minerals (e.g., *Littorina*), *Fusinus* is entirely of calcite. *Pteropoda* are chiefly aragonite. *Porifera* (sponges) are composed both of calcite (calcareous sponges) and silica. Most *cephalopod* remains are composed of aragonite, but the guard of *belemnites* is of calcite. Replacement of such original organic substance by silica, limonite, marcasite or pyrite, rarely by calcium sulphate, barite, etc., is possible.

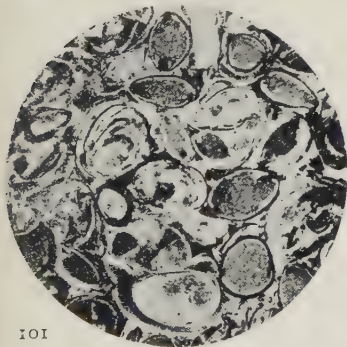
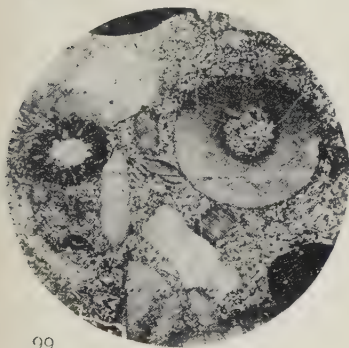
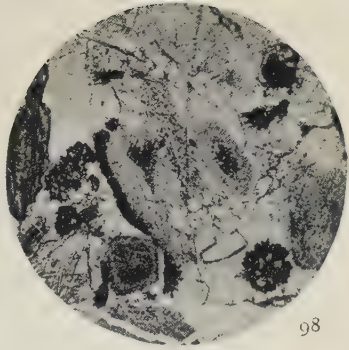
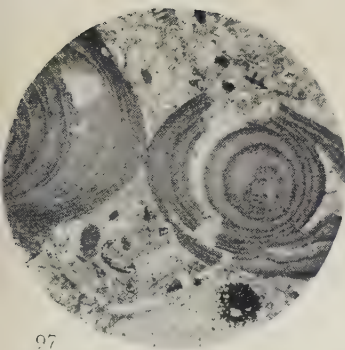
Mech. Comp. Concerns only detrital ingredients which are usually very fine, between 0.1 mm. and 0.01 mm.

Micro. Investigations of limestones in thin section should proceed methodically. Where organic remains are present, study these first. The arrangement of the mineral substance forming the shells or hard parts may be concentric, radial, tangential or combinations of these. Radial arrangement results in the "black cross" effect in doubly polarised light. Sometimes the shell-fragments are thick, cloudy or opaque. Micro-organisms, e.g., *foramanifera*, *algæ*, *radiolaria*, *diatoms*, etc., are always significant and often well preserved, either as original carbonate or silica, or replaced by pyrite, glauconite, etc. Calcite and aragonite as fossil-shell substance are often impossible to differentiate positively under the microscope: see p. 133. Next investigate the matrix of the rock. If megascopic or larger microscopic organisms are plentiful, this may be reduced to enveloping or interstitial material; with impoverishment of visible organisms, the matrix dominates and characterizes the rock. Usually it presents a

mosaic of mutually interferent calcite crystals representing coarsely or finely recrystallized calcareous mud; sometimes the muddy character prevails, when much of the cement is optically inert; it shows up well by reflected light, however. Veins of secondary silica, deep bluish-grey birefringence tint, or of interlocking quartz crystals, may also traverse the rock, or may be distributed haphazardly in the calcite cement. Colouring matter denotes impurity, usually due to iron compounds. Detrital matter should be searched for under high power objective in the cementing medium, (alternatively isolated by crushing the rock (p. 73)); this examination may also reveal minute organisms scattered through the mass. Every transition from the normal limestone to dolomitic, oolitic and other types must be anticipated and will be easily decipherable under the microscope. The structure of limestones is primarily determined by the relationship of organic fragments or of prolific micro-organisms to the matrix, or, where organisms are lacking, by the arrangement of the components of the matrix, presence or absence of definite orientation, or by special developments (e.g., oolites, p. 314). Careful scrutiny of the closeness or sparseness of spacing of the fossil elements in the cement is significant, often diagnostic for a particular horizon in the limestone formation. Similarly the manner of distribution of micro-organisms in a finely divided matrix should be noted. Secondary structures determined by mineral veins, argillaceous matter in bands, patches of siliceous material, chert development, etc., should all be carefully investigated.

The results of microscopic examination, by determination of specific organisms characteristic of the rock, lead to its correct definition. Thus the following varieties may be separated, each distinguished by the presence to a greater or lesser extent of the forms identified:—

- a. *Algal limestone*, e.g., *Lithothamnion* and *Chara* limestones.
- b. *Bryozoan limestone*, e.g., *Fenestella* limestone.
- c. *Coral limestone*, e.g., *Alveolite* limestone.
- d. *Crinoidal limestone*, e.g., *Encrinite* (*Encrinus*) limestone.
- e. *Crustacean limestone*, e.g., *Ostracod* limestone.
- f. *Echinoid limestone*, e.g., *Nucleolite* (*Echinobrissus*) limestone.



LIMESTONE.

- FIG. 97. Algal Limestone (*Lithothamnion*, etc.), Pemba I., E. Africa. [x 16.]
 " 98. Coral Limestone (Silurian). Wenlock Edge, Salop. [x 20.]
 " 99. Crinoidal Limestone (Carboniferous), Skrinkle Bay, Pembroke. [x 15.]
 " 100. Nummulitic Limestone (Eocene), Cairo, Egypt. [x 15.]
 " 101. Ostracod Limestone (Purbeckian), Swanage, Dorset. [x 15.]
 " 102. Shelly Limestone, "Purbeck Marble" (Purbeckian), Purbeck, Dorset. [x 15.]

- g. *Foraminiferal limestone*, e.g., *Nummulitic limestone*.
 h. *Shelly limestone*, made up largely of miscellaneous fossil-shell fragments, chiefly *mollusca* and *brachiopoda*.

With increase of impurity in the form of argillaceous matter, the so-called "argillaceous limestone" or "cement-stone" is produced. This variety embodies the normal features of limestone, but the matrix contains a good deal of finely divided clay-substance, much of it optically inert; sometimes the clay-substance is distributed regularly throughout the rock, in other cases it occurs in patches, often enclosing visible detrital quartz.

Types. Cambrian, Durness Limestone, N.W. Highlands of Scotland, Skye, etc., with sponge remains, sometimes partially dolomitised, some examples "saccharoidal";¹ Ordovician, Bala Limestone, Bala, North Wales, with calcareous and siliceous mud, crinoids, polyzoa, etc.;² also the Corona Beds (of same age), Cross Fell, Westmorland, crustacean limestone (*Beyrichia*);³ Silurian, Wenlock Limestone, Shropshire, often impure rock with abundant corals, also crinoids and polyzoa;⁴ Aymestry Limestone, Silurian, Shropshire, earthy limestone with brachiopods ("Pentamerus (*Conchidium*) Limestone");⁵ Devonian limestone, Devonshire, corals and crinoids;⁶ Old Red Sandstone "Cornstone," Welsh Borders, nodular, argillaceous limestone, much amorphous matter;⁷ Carboniferous Limestone, Bristol district, Forest of Dean, etc., crinoidal and shelly limestone;⁸ Lias, Barrow-on-Soar, Leicestershire, argillaceous limestone ("Cement Stone") with shell-fragments, fish scales, etc.; Portlandian, massive limestone, often with much calcareous mud, shell-fragments, secondary silica, etc.; Purbeckian (Upper Purbeck) "Marble," Dorset, Wilts, etc.; freshwater limestone with gasteropod (*Paludina*) and lamellibranch fragments (*Cyrena*, *Unio*, etc.), also plant remains;⁹ Eocene, Cairo, Egypt, foraminiferal limestone ("Nummulitic Limestone"); Oligocene, Bembridge Limestone, marly or concretionary, freshwater limestone with *algæ* (*Chara*), gasteropods and curious oviform bodies, said to be "the eggs of the large *Amphidromus*."¹⁰

Ref. ¹ *Geology N.W. Highlands, Mem. Geol. Surv. Scot.*, 1907, p. 375.

² A. J. Jukes-Browne, *Stratigraphical Geology*, 1912, p. 125.

³ J. E. Marr, *Geol. Mag.*, 1892, p. 97.

⁴ A. J. Jukes-Browne, *op. cit.*, p. 165; A. Harker, *Petrology for Students*, 1919, p. 236.

⁵ A. J. Jukes-Browne, *op. cit.*, p. 167.

⁶ E. Wethered, *Q.J.G.S.*, xlviii., 1892, p. 377.

⁷ A. Heard & R. Davies, *Q.J.G.S.*, lxxx., 1924, p. 504.

⁸ E. Wethered, *Geol. Mag.*, 1886, pp. 529-540.

⁹ W. R. Andrews & A. J. Jukes-Browne, *Q.J.G.S.*, l., 1894, p. 59, (Vale of Wardour); A. Strahan, *Geology of Isle of Purbeck, Mem. Geol. Surv.*, 1898, pp. 79, 80; H. B. Woodward, *Jurassic Rocks of Britain, Mem. Geol. Surv.*, v., 1894.

¹⁰ J. W. Judd, *Q.J.G.S.*, xxxvi., 1880, p. 169; also E. Keeping, *Geol. Mag.*, 1887, p. 48; A. J. Jukes-Browne, *op. cit.*, p. 561.

General References.

J. G. Goodchild, *Geol. Mag.*, 1890, p. 71.

E. W. Skeats, *Bull. Mus. Comp. Zool. Harvard*, xlii., 1903, p. 53.

H. C. Sorby, *Q.J.G.S.*, xxxv., 1879, pp. 56-95.

(B1. 2) DOLOMITIC LIMESTONE.

[Figs. 103-5, Pl. xxviii.]

Lith. The true dolomitic limestone is one containing the mineral dolomite, but in which calcium carbonate predominates. In outward appearance there is often nothing specific to suggest the presence of dolomite, and even under the microscope, if the familiar dolomite "rhombs" are not developed, diagnosis may not be positive in the absence of chemical test (p. 146). On the other hand, many dolomitic limestones are sufficiently distinctive in microscopic characters to warrant the separation of the type from ordinary limestones. Megascopic characters of dolomitic limestones include compactness, closeness of grain, cellular structure, usually a white, cream or grey colour; their appearance *en masse* is often nodular, concretionary, thick bedded, conspicuously jointed, sometimes massive. Organic remains are common, but may be obliterated by dolomitisation; they often show a ten-

dency to weather out on the surface of the rock, *e.g.*, sponge limestone (Durness dolomitic limestone, Skye, N.B.).¹ Bedding may or may not be apparent in the hand-specimen.

Text. Usually medium to fine; sometimes earthy.

Shape. Concerns detrital particles only: usually rounded. In so far as dolomite is concerned, this mineral often builds very perfect rhombs, producing a highly angular mosaic.

Min. Comp. *Al.* As for limestone (BI. 1, p. 308).

Au. Calcite, dolomite, silica, hæmatite, limonite, less commonly argillaceous matter and carbon; also sulphates.

Organic material. As for limestone, but *foramini-fera*, corals and *polyzoa* tend to predominate.

Mech. Comp. Detrital constituents usually very fine: <0.05 mm.

Micro. Under the microscope every stage from incipient to partial or complete dolomitisation can be traced. Incomplete dolomitisation usually implies the change subsequent to deposition of the original limestone; complete dolomitisation implies contemporaneous process with deposition. In the case of complete achievement, much of the original organic remains may be obliterated and specific identification be thereby rendered impossible; in such examples the dolomite assumes a crystalline or granular form. Where partial change is manifest, the dolomite is detected for the greater part in the matrix; if crystalline (in rhombs) it will be at once apparent; if granular or disseminated as fine dolomitic mud, it may be amorphous or almost cryptocrystalline, when staining will be necessary for its differentiation from calcite. In some examples dolomite rhombs or other crystal forms show the presence of impurities such as hæmatite, arranged in geometrical fashion sympathetically with the outlines of the crystal. Secondary silica is often noted in the interstices of the crystals. Alternatively, where the limestone was originally impure with admixture of argillaceous matter, this is seen to form a dirty, usually impenetrable background to the dolomite mosaic. Secondary silicification of dolomitic limestone occurs. Another feature of this type of limestone is the presence of cracks, sometimes widened to gaps of large size, which may or may not be filled with secondary

calcite, quartz or other mineral, *e.g.*, barite, anhydrite; such veins are in the nature of shrinkage-cracks, determined by the volume-contraction of 12.3% with complete dolomitisation. The association of anhydrite, gypsum, rock-salt, etc., with certain dolomitic limestones suggests inorganic origin, *i.e.*, precipitation in land-locked saline waters (p. 442).

Types. Cambrian, Durness Limestone, N.W. Highlands of Scotland, Skye, etc., pure limestone with sponge remains, partial dolomitisation;¹ Devonian limestone, Devonshire, partial dolomitisation with rhombs picked out with iron oxide;² Permian Magnesian limestone, complete dolomitisation, granular dolomite, few organic remains recognizable;³ Triassic Dolomites, Southern Tyrol, massive, unstratified dolomitic limestone, chiefly algal and echinoderm organisms.⁴

Ref. ¹ *Geology N.W. Highlands, Mem. Geol. Surv. Scot.*, 1907, p. 375.

² E. Wethered, *Q.J.G.S.*, xlviii., 1892, pp. 377-387.

³ D. Woolacott, *Q.J.G.S.*, lxvii., 1911, p. 312; also *Geol. Mag.*, 1919, pp. 452, 485.

⁴ E. W. Skeats, *Q.J.G.S.*, lxi., 1905, pp. 97-141.

General References.

F. M. Van Tuyl, *Iowa Geol. Surv.*, xxv., 1914, pp. 371-373.

W. H. Twenhofel, *Treatise on Sedimentation*, 1926, p. 251 & refs. cited.

R. C. Wallace, *Cong. Geol. Inter., C.R.*, xii. (1913), 1914, p. 875.

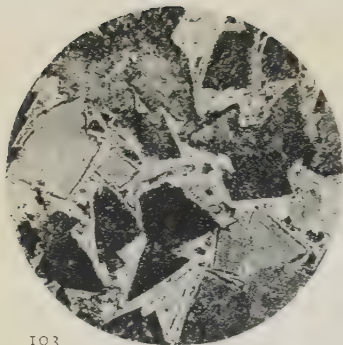
L. M. Parsons, *Geol. Mag.*, 1918, p. 246.

Rep. of the Coral Reef Committee, Royal Society, 1904.

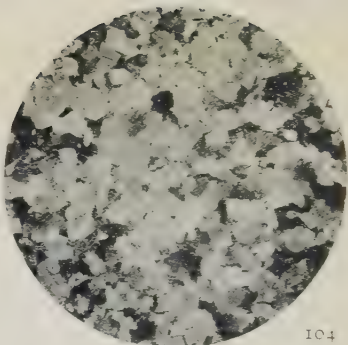
(B1. 3) OOLITIC AND PISOLITIC LIMESTONE.

[Figs. 106-8, Pl. xxviii.]

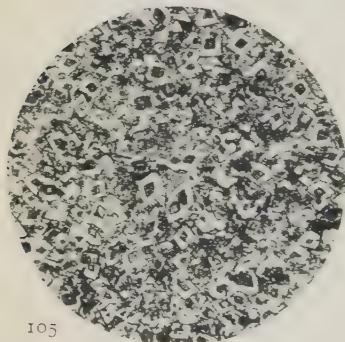
Lith. These are special but commonly developed types of limestone in which the bulk of the rock is composed of spheroidal or ellipsoidal grains of calcium carbonate; such grains exhibit concentric (successive) growths of the carbonate about an organic or inorganic nucleus. The smaller developments, 1 mm. (or less) up to 2 mm. in diameter, are the oolites; larger grains, up to the size of a pea or even larger, are the pisolites. Very coarse pisolites are sometimes erroneously termed "grits," *e.g.*, "Pea Grit." Both types are readily recognized



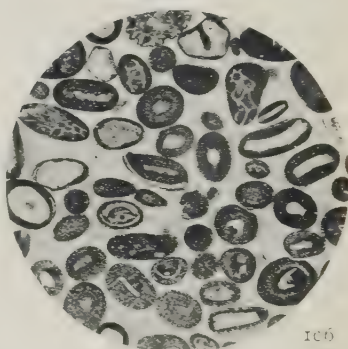
103



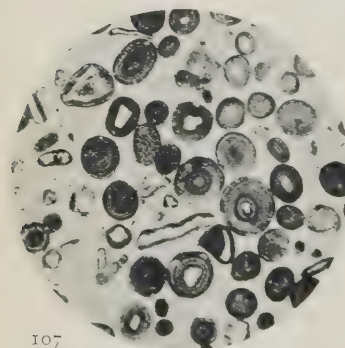
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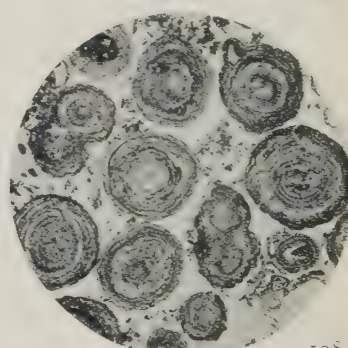
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107



108

DOLOMITIC, OOLITIC AND PISOLITIC LIMESTONES.

FIG. 103. Dolomitic Limestone (Permian), Mansfield Woodhouse, Notts. [x 15.]

„ 104. Dolomitic Limestone (Palæozoic), Malew, I.O.M. [x 23.]

„ 105. Dolomitic Limestone (Carboniferous), Burlescombe, Somerset. [x 42.]

„ 106. Bath Oolite (Bathonian), Farley, nr. Bath. [x 15]

„ 107. Osmington Oolite (Corallian), Osmington, Dorset. [x 20.]

„ 108. Pisolitic Limestone (Silurian), Malvern. [x 9.]

by these distinguishing megascopic characters. The oolites and pisolites may be closely packed together, or they may be scattered haphazardly through a finer matrix. Organisms extremely common. Bedding frequent. Colour varies from white in the purest forms of limestone to yellow, brown and red. Secondary calcite and/or silica often noted in the hand-specimen.

Text. Coarse to medium; rough; earthy or rubbly with conspicuous matrix.

Shape. Oolites spheroidal or ellipsoidal; pisolites more irregular, sometimes flattened resembling large nummulites. Detrital constituents SA.

Min. Comp. Al. Quartz, iron-ores, and often surprisingly varied accessory mineral suite in the impure types.

Au. Calcite, siderite, dolomite, silica, hæmatite, limonite. Oolites and pisolites of fine calcareous mud, sometimes crystallized; silicified oolites not uncommon.

Organic material. Shell-fragments, *foraminifera*, crinoid stems, *polyzoa*, etc.

Mech. Comp. Detrital constituents usually of the silt grade. Oolite and pisolite dimensions as above.

Micro. Oolitic and pisolitic limestones, especially the former, are among some of the most striking varieties of sedimentary rocks met with under the microscope. The oolites themselves first attract attention; examine for nucleus, which may be a detrital quartz grain, shell-fragment or *foraminifer*; in many cases it is represented by a mud particle; sometimes no nucleus is determinable. Concentric layers of carbonate are revealed, often picked out by ferriferous impurity; in some examples radial structure is observed. These oolite grains, together with shell-fragments and free organisms, are set in a fine matrix which, in the purest types, is seen to be composed of a crystalline mosaic of calcite occurring in mutually interferent particles; this matrix is frequently stained with limonite or hæmatite and spotted with iron oxide. Quartz is common, increasing with the more earthy types. Sometimes much of the centre of the oolite grain is replaced by calcite of the same character as the matrix. These remarks apply equally to the pisolitic types. In structure, apart from the special developments under discussion, note should be taken of the proportion of oolites or pisolites to matrix; where the latter predominates derivation of the former

from pre-existing oolitic or pisolitic rocks may be suggested.

Types. Ordovician, Hirnant Limestone, Bala district, N. Wales, oolites partly replaced by chalcedonic silica and layers picked out with carbon dust;¹ Silurian, Wenlock Limestone, Malvern, oolites scattered in calcareous-argillaceous matrix; Carboniferous Limestone, Gloucestershire, etc., oolitic rock with *Girvanella*;² Inferior Oolite, Gloucestershire, both oolitic and pisolitic examples, the former with abundant organic remains, the latter ("Pea Grit") characterized by *Girvanella*;³ Great Oolite, Malton, Yorkshire, Northamptonshire, etc., scattered oolite grains in recrystallized calcite matrix; also Bath Oolite (Great Oolite), Bath, Somersetshire, compact oolitic type; Corallian, Osmington Oolite, a perfect example of a closely packed, pure oolite;⁴ Portlandian, Portland Oolite, Portland, Dorset.⁵

Ref. ¹ L. W. Fulcher, *Geol. Mag.*, 1892, pp. 114-117.

² E. Wethered, *Q.J.G.S.*, xlv., 1890, p. 271.

³ E. Wethered, *op. cit.*, p. 274.

⁴ J. H. Blake & W. H. Hudleston, *Q.J.G.S.*, xxxiii., 1877, p. 265; E. Wethered, *op. cit.*, p. 278; A. Strahan, *Geology of Isle of Purbeck, etc.*, *Mem. Geol. Surv.*, 1898, p. 37.

⁵ Harris, *Proc. Geol. Assoc.*, xiv., 1895, p. 72.

General References.

J. J. H. Teall, *Jurassic Rocks of Britain*, *Mem. Geol. Surv.*, iv., 1894.

F. M. Van Tuyl, *Journ. Geol.*, xxiv., 1916, p. 792.

W. H. Butcher, *Journ. Geol.*, xxvi., 1918, p. 593.

G. W. Tyrrell, *Principles of Petrology*, 1926, p. 227.

(Bi. 4) **ABYSSAL OOZE** (CALCAREOUS). [Fig. 109, Pl. xxix.

Lith. Under this heading is included all deep-sea oozes of predominantly calcareous character. They are in the main composed of the hard parts of free-swimming pelagic organisms such as *foraminifera*. The two important examples are Globigerina Ooze and Pteropod Ooze. Dredged samples (*e.g.*, Challenger Expedition) are white to buff-coloured when dry and have the appearance of very fine powder. The organisms are usually too minute to be seen with the naked eye.

Text. Exceedingly fine, homogeneous, "soapy."

Shape. Detrital particles when present A.

Min. Comp. Al. Felspar, augite, olivine, hornblende, quartz, magnetite, volcanic glass, rock-fragments, etc.

Au. Lime carbonate, silica, magnesite, traces of phosphate, sulphate.

Mech. Comp. Detrital and other inorganic particles <0.01 mm, but highly variable.

Micro. Globigerina ooze is composed principally of the tests of *globigerina* and other *foraminifera*, usually with a small proportion of siliceous organisms, e.g., *radiolaria*, *diatoms*. In addition characteristic disc-like bodies termed *coccoliths* are observed; these are calcareous parts of certain *algæ* (*coccospheres*). Another form of similar origin is the *rhabdolith*, a long slender T-shaped body, not unlike a sponge spicule. Organic matter makes up the bulk of the fine washings of this ooze, though the mineral constituents are normally quite conspicuous, constituting from 3 to 4 per cent. The inorganic matter resembles the abyssal red clay (see A3. 5, p. 294). The pteropod ooze is composed principally of *pteropod* shells and *heteropod* (pelagic gasteropods), together with *foraminifera* and a small percentage of siliceous organisms. This type of ooze is much more variable in character than the globigerina ooze, though there is about the same amount of mineral matter. *Coccoliths* and *rhabdoliths* are found. Both the pteropod and heteropod shells are very delicate and exhibit beautiful forms; much broken and fragmental material is characteristic. Samples relieved of the fine calcareous mud by careful washing are best studied with a binocular microscope, using dark-ground illumination.

Types. Globigerina and Pteropod Ooze, Challenger Expedition.¹

Ref. ¹ J. Murray & A. F. Renard, *Deep Sea Deposits, Challenger Report*, 1891.

(B1. 5) **CHALK.**

[Figs. 110-11, Pl. xxix.

Lith. An exceedingly pure form of limestone varying from soft, almost incoherent material to compact, hard rock. White, yellow to grey in colour, the latter implying some admixture of clay material; strongly glauconitic varieties are greenish-grey. Usually homogeneous and well stratified, but bedding not apparent in small specimens. Megascopic organisms are mainly molluscan

fragments, especially parts of *Inoceramus*; many other fossils, however, are characteristic, often beautifully preserved. Calcite veins observed in the harder varieties. Flint nodules and marcasite concretions common at certain horizons. Black staining, usually on joint-surfaces, due to manganese oxide.

Text. Fine, compact or friable.

Shape. Detrital particles A to SA. Quartz often well rounded.

Min. Comp. Al. Rare. Quartz, ilmenite, tourmaline, zircon, staurolite, locally chromite (p. 160).

Au. Calcareous mud, secondary silica, limonite, glauconite.

Mech. Comp. Chalk particles are exceedingly fine in grade and remain suspended in water for considerable time. Detrital grains usually <0.01 mm.

Micro. Hard chalk is best studied by means of thin sections in addition to its investigation in the form of powdered material. The softer varieties are examined as incoherent rocks and may with advantage be washed free of much of the finest mud. For inorganic components the soluble carbonate should be eliminated with acid and the residue segregated. Microscopical examination of chalk shows that it is made up partly of micro-organisms, mainly of very fine calcareous matter and, in the impure varieties, of clay-substance and detrital minerals; the latter are normally scanty. Micro-organisms include *foraminifera*, especially chambers of *globigerina*, *coccoliths*, *rhabdoliths* (p. 317), sponge spicules and less commonly *radiolarian* tests. The fine white mud may be due to disintegrated fossil shells or possibly to precipitation from solution. Glauconite frequently fills the chambers of the *foraminifera* present, or otherwise preserves original structures; its partial alteration to limonite is often observed. Other infilling material may be calcite, in well crystallized mosaic, or chalcedonic silica. Detrital grains are interesting on account of their comparative scarcity and varied nature.

Types. Cretaceous: Lower Chalk, Wiltshire, Dorset, etc., "Chloritic Marl," a sandy, glauconitic variety;¹ Chalk Marl, with clay material;¹ "Belemnite Marl," a soft grey chalk with belemnites (*actinocamax plenus*), etc.;² "Totternhoe Stone," dark grey chalk with green-coated nodules (base) and

abundant shell-fragments up to 60 or 70 per cent. of the rock;³ Middle Chalk, white, nodular, rough or lumpy; "Melborne Rock," hard, nodular chalk;⁴ Upper Chalk with flints, white, powdery, nodular or in layers. (N.B.—The so-called Red Chalk of Hunstanton, Norfolk, is of Selbornian age, and consists of an argillaceous limestone containing abundant red oxide of iron).⁵

Ref. ¹ W. Hill, *Cretaceous Rocks of Britain*, *Mem. Geol. Surv.*, ii., 1903, chs. xxii., xxiii., xliii., also iii., 1904, ch. xxii.

² W. Hill, *Q.J.G.S.*, xliv., 1888, p. 320 *et seq.*

³ A. J. Jukes-Browne, *Stratigraphical Geology*, 1912, p. 504.

⁴ W. Hill & A. J. Jukes-Browne, *Q.J.G.S.*, xlii., 1886, p. 216.

⁵ W. Hill, *op. cit.*, i., 1900, pp. 345-6.

General References.

W. Hume, *Q.J.G.S.*, liii., 1897, pp. 568-584.

A. J. Jukes-Browne, *Proc. Yorks. Geol. Soc.*, xii., 1895, pp. 385-395.

W. A. Tarr, *Geol. Mag.*, lxii., 1925, p. 252.

I. C. Double, *Journ. Roy. Micros. Soc.*, 1927-8.

(B2) SILICEOUS DEPOSITS. This division includes such consolidated rocks as chert and flint, the abyssal oozes depending mainly on the accumulation of organisms such as *radiolaria*, diatoms and sponge skeletons, and the curious "silica earth" deposits, likewise of organic origin. In the case of chert and flint it is admitted that the entirely organic origin of these deposits is open to question, and silica derived from chemical reaction may and does play an important part in their formation (p. 352). For the most part, however, these deposits exhibit so much definitely identifiable organic matter that its predominating influence is seldom in doubt. The following types are recognized:—

(B2. 1) Chert and Flint (p. 320).

(B2. 2) Abyssal Ooze (p. 321).

(B2. 3) Siliceous Earth (p. 322):

(Bz. 1) **CHERT AND FLINT.*** [Figs. 112-14, Pl. xxix.]

Lith. The difference between chert and flint is probably more apparent than real, and to some extent is a matter of nomenclature. Both rocks are essentially pure developments of chalcedonic silica occurring in the form of nodules, concretions or bedded layers in calcareous deposits such as limestone. In British stratigraphy the term "chert" applies for the most part to such rocks present in pre-Chalk horizons; flint is restricted to the real Chalk occurrences and to those rudaceous deposits derived therefrom. In external appearance both chert and flint are very similar when fresh, though the former has a more decided splintery fracture, the latter a conchoidal fracture. When fresh, both flint and chert may be blue-grey or indigo in colour; weathering and exposure to atmospheric conditions bring about obvious changes both in colour and appearance (patination). Chert often assumes a "sugary" appearance; flint, a worn, pale-coloured porcellanous aspect. Chert is often traversed by a network of cracks filled with secondary silica and stained with limonite or hæmatite; flint is less commonly susceptible to these developments. The interior of a chert nodule is usually solid, often a fossil-shell nucleus or aggregate of fossil particles; the interior of a flint, on the other hand, may be quite hollow, and from it a siliceous powder, full of sponge spicules, etc., may often be obtained.

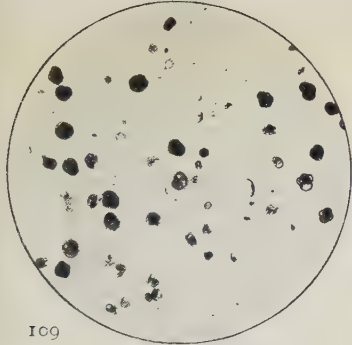
Text. Extremely fine, smooth; rough on weathered surface.

Shape. As nodules or concretions, both chert and flint assume diverse shapes, often occurring in most fantastic forms.

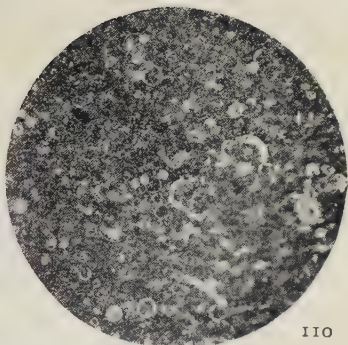
Min. Comp. Silica, mainly chalcedony; in flint occasionally opaline silica. Limonite staining.

Micro. The microscopical examination of chert depends largely on the age of the material and on its condition as regards weathering. Some varieties, *i.e.*, Portland Chert (Upper Jurassic), as with flint from the Upper Chalk, are almost optically inert and very little, save certain ill-defined organic remains, can be made out. In most cases, however, some degree of crystallization or cryptocrystalline structure can be ascertained, especially in cherts. When well preserved, the

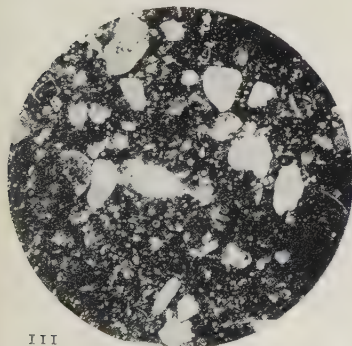
* Only in part referable to organic origin: see p. 352.



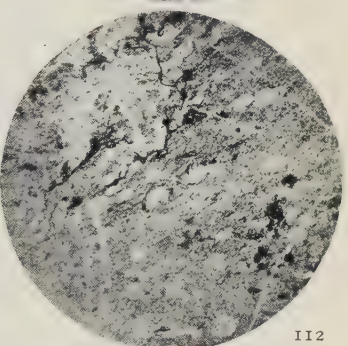
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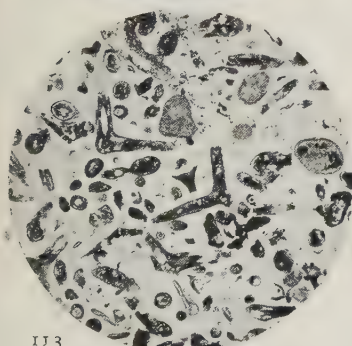
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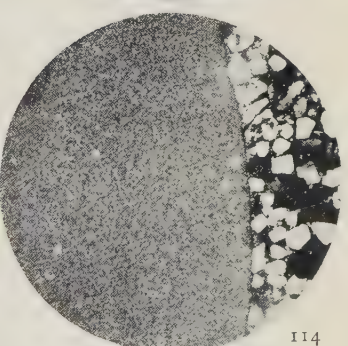
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112



113



114

ABYSSAL OOZE, CHALK, CHERT AND FLINT.

- FIG. 109. Globigerina Ooze, N. Atlantic Ocean, 1,260 fms. [x 23.]
 " 110. Chalk (Cretaceous), Larne, Antrim. [x 35.]
 " 111. "Chloritic" Marl, Bincombe, nr. Weymouth, Dorset. [x 17.]
 " 112. Radiolarian Chert (Ordovician), Mullion I., Cornwall. [x 23.]
 " 113. Portland Chert (Portlandian), Swanage, Dorset. [x 15.]
 " 114. Flint, pebble in sandstone (Eocene), Hertfordshire "Pudding Stone." [x 15.]

spherical tests of *radiolaria*, or the characteristic sponge spicules, are easily diagnosed, but in many so-called radiolarian cherts, the dominant organism is only represented by a blurred spherical structure which has to be taken very much on trust. Every stage between the inert chalcedonic silica, the faint reaction with doubly polarised light, to the fine mass of mutually interferent silica particles of brilliant blue-grey or yellow polarization tints, is discernible in cherts; flint seldom exhibits striking polarisation phenomena unless markedly weathered. Chert replacement of oolitic or shelly limestone is not uncommon.

Types. Ordovician, Radiolarian Chert, South Scotland;¹ Radiolarian Chert of same age (?), Mullion Island, Cornwall;² Portland Chert, Dorset;³ Upper Cretaceous flint (zone of *Micraster coranguinum*, Upper Chalk), Kent, Cambridgeshire, etc.;⁴ Pleistocene, gravels from Thames basin: flints showing different degrees of weathering, some with hollow centres, spicule-dust, etc. G. M. Lees has described some interesting brecciated, banded and replacement cherts from Palestine, the latter type including some remarkable coprolite silicifications.⁵

Ref. ¹ G. J. Hinde, *Ann. Mag. Nat. Hist.*, vi., 1890, pp. 41-47; C. Lapworth, *Geol. Mag.*, 1889, pp. 20, 69.

² G. J. Hinde, *Q.J.G.S.*, xlix., 1893, p. 215; H. Fox & J. J. H. Teall, *Q.J.G.S.*, xlix., 1893, p. 211; J. S. Flett & J. B. Hill, *Geology of the Lizard, etc.*, *Mem. Geol. Surv.*, 359, 1912, p. 172 & refs. cited.

³ A. Strahan, *Geology of Isle of Purbeck, etc.*, *Mem. Geol. Surv.*, 1898.

⁴ W. Hill, *Cretaceous Rocks of Britain*, *Mem. Geol. Surv.*, iii., 1904.

⁵ G. M. Lees, *Proc. Geol. Assoc.*, xxxix., 1928, p. 445 *et seq.*

General References.

W. Hill, *Proc. Geol. Assoc.*, xxii., 1911, p. 61.

W. A. Richardson, *Geol. Mag.*, 1919, p. 535.

W. H. Twenhofel, *Treatise on Sedimentation*, 1926, p. 378 *et seq.*

(B2. 2) **ABYSSAL OOZE** (SILICEOUS). [Figs. 115-16, Pl. xxx.
Lith. Ooze of siliceous character owes its origin chiefly to radiolarian tests, diatom frustules or sponge

spicules, or to a combination of these. Such ooze is seldom pure, but contains admixture of calcareous organisms (Br. 4, p. 316) and volcanic mud (A3. 5, p. 294). The organisms are not discernible with the naked eye; the material is homogeneous, white, yellow or red in colour, and of the consistency of flour. Normally incoherent when dry.

Text. Extremely fine.

Shape. Detrital particles A.

Min. Comp. Al. Quartz, felspar, augite, hornblende, fragments of pumice, magnetic iron particles, volcanic rock-fragments, etc.

Au. Silica, oxide of iron, calcareous matter, manganese grains, etc.

Mech. Comp. Detrital matter varies between 0.15 mm. and 0.01 mm., or less.

Micro. Under the microscope radiolarian ooze is characterized by the tests or skeletons of these organisms; such skeletons exhibit either lattice-like or reticulate structure and are usually spherical, elongated, and with or without spines. These organisms constitute 20 per cent. of the ooze (or more) in typical examples. In the diatom ooze, the siliceous frustules of these vegetable organisms occur in spherical, polygonal, vermiform and other shapes, and are associated with calcareous organisms and terrigenous matter. Sponge ooze is a distinctive deposit, composed principally of spicules of varying shape, 3-rayed, 4-rayed, multi-rayed types, etc., or as single spicules (monaxonid). Most of these spicules are isotropic between crossed nicols, though with process of time cryptocrystalline silica is noted. The washings from siliceous ooze are made up chiefly of calcareous and siliceous mud in about equal proportions.

Types. Radiolarian Ooze, Pacific and Indian Oceans, etc.;¹ Diatom Ooze, Indian Ocean, North Atlantic Ocean, etc.;² Sponge Ooze, various deep sea deposits.

Ref. ¹ J. Murray & A. F. Renard, *Deep Sea Deposits*, *Challenger Report*, 1891, p. 203 *et seq.*

² *Ibid.*, p. 208 *et seq.*

(B2. 3) SILICEOUS EARTH.

[Fig. 117.

Lith. In this category fall the following rocks:—Radiolarian Earth, Barbados Earth, Diatomaceous Earth (Diatomite=Kieselguhr), Infusorial Earth (of

much the same composition as Diatomite). Tripoli, sometimes confused with diatomaceous earth, is a

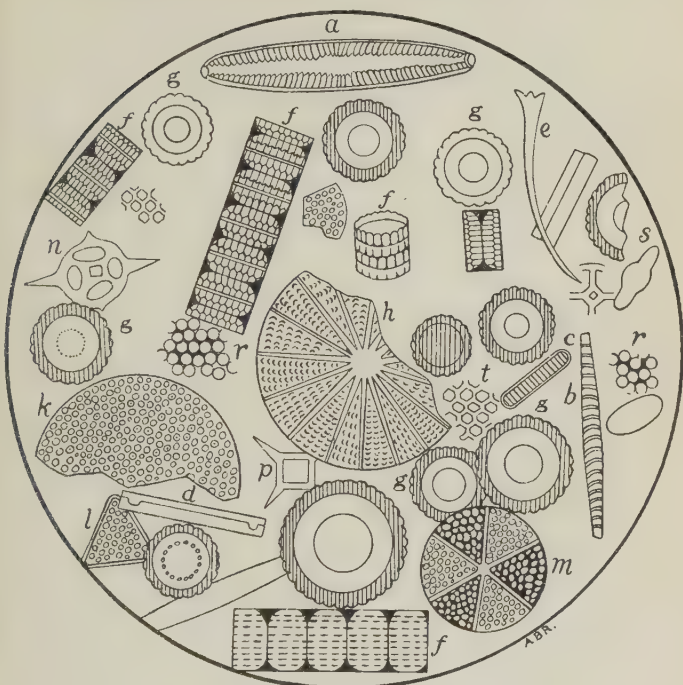


FIG. 117. Infusorial Earth, Richmond, Virginia, U.S.A.

(After J. D. Dana.)

a, *Pinnularia perigrina*; *b*, *c*, *Odontidium pinnulatum*; *d*, *Grammatophora marina*; *e*, *Spongiolithis appendiculata*; *f*, *Melosira sulcata*; *g*, transverse view of *f*; *h*, *Actinocyclus Ehrenbergii*; *k*, *Coscinodiscus apiculatus*; *l*, *Triceratium obtusum*; *m*, *Actinoptychus undulatus*; *n*, *Dictyocha crux*; *p*, *Dictyocha*; *r*, fragment of *Actinoptychus senarius*; *s*, *Navicula*; *t*, fragment of *Coscinodiscus gigas*.

residual product derived from decomposition of siliceous limestone. These earths are fundamentally similar

to the oozes (B2. 2), but are formed under different conditions and, moreover, are partially consolidated. For instance, diatomite is produced by the accumulation of diatom frustules in shallow lakes and swamps in contrast to the abyssal environment of the ooze composed of much the same organic material. The earths are usually white, cream, or when impure highly coloured, buff, brown, red; they are homogeneous, pulverulent, and have a decidedly earthy "feel" and appearance.

Text. Very fine, powdery, friable, earthy.

Shape. A.

Min. Comp. Al. Usually a conspicuous detrital assemblage varying considerably in nature and quantity. Quartz, iron-ores, zircon, tourmaline, garnet, etc.

Au. Silica, limonite, hæmatite, calcareous matter, carbonaceous material, manganese, etc.

Mech. Comp. Often remarkably uniform, ± 0.05 mm.

Micro. Most examples of these particular rocks can be studied both in thin section and as incoherent materials. The radiolarian earth is composed principally of radiolarian tests (p. 321), diatom frustules and sponge spicules; calcareous organisms are infrequent or absent, but calcareous matter is invariably detected by the "twinkling" reaction. The organisms, as in Barbados Earth, are set in "a felted mass of interlacing fragments of radiolaria and sponge spicules."¹ In the case of Diatomite, the principal ingredients are diatom frustules with apparent mineral matter, clay, and other micro-organisms. Infusorial Earth is a fine white powder, mainly diatoms, with silica and a little calcite, characterized by its extreme homogeneity. These plant remains assume spherical, cylindrical, cellular and triangular shapes and usually comprise many different recognizable species. In some examples, a few *polycystines* (*siliceous foraminifera*) occur.

Types. Recent and Tertiary Radiolarian Earths, Barbados, Trinidad, B.W.I.;¹ Recent Diatomite, Skye, Aberdeenshire, etc., N.B.;² Tertiary, Richmond, Virginia, U.S.A., Infusorial Earth.³

Ref. ¹ A. J. Jukes-Browne & J. B. Harrison, *Q.J.G.S.*, xlviii., 1892, pp. 174-5.

² *Mem. Geol. Surv., Spec. Rep. Min. Resources, Gt. Brit.*, v., 1916, pp. 35-37.

^s J. D. Dana, *Manual of Geology*, 1876, p. 496, fig. 882.

General Reference.

N. Goodwin, *Bibliography of Diatomaceous Earth*, *Chem. Met. Eng.*, xxiii., 1920, pp. 1158-60.

(B3) FERRUGINOUS DEPOSITS. Recent research on sedimentary iron-ores, more especially the bedded iron-ores of England and Wales by A. F. Hallimond,¹ has shown conclusively the dominating influence of chemical reaction and precipitation in the formation of these deposits. For this reason these rocks are more logically considered under the heading of chemically-formed deposits (C), (p. 344). On the other hand, due recognition of the important part played by bacteria in the chemical processes, and the belief in certain cases that iron deposits are due directly to organic origin of this kind, make it advisable to retain a place in the present scheme under the heading of organically-formed deposits, more especially in view of the fact that considerable research is still in progress to determine the precise nature of the organic reactions known to take place. This is but another instance of the difficulty of fitting all sedimentary rock-types into "water-tight" compartments, not that the author admits either the practice or desirability of so doing in this book.

A. F. Hallimond,² writing on this subject, says, "The role of the 'iron bacteria' in the formation of the iron ores has lately received much attention, but it seems likely that this small group represents only a fraction of the organisms concerned and that the action of the ordinary types

¹ *Mem. Geol. Surv., Spec. Rep. Min. Resources, Gt. Brit.*, xxix., 1925.

² *Op. cit.*, p. 14.

of bacteria is of no less significance and of far wider extent . . . the crystalline nature of the rocks as seen in the micro-section rarely offers the suggestion of anything but a purely inorganic reaction. Such a system is, nevertheless, not at variance with the theory of bacterial action. . . . Iron and other inorganic materials may not play a part in the structure of the organism itself, but they will be affected in various ways according to the products yielded by the organism, so that, for example, the reduction of ferric oxide and the production of carbon dioxide in quantity may depend entirely on the existence of suitable organisms which need not themselves be iron-secreting. The insoluble compounds of the inorganic materials are, however, very limited in number, so that the ores precipitated cannot present a chemical or mineralogical variety at all comparable with the variety of organisms that may be concerned. In this way it seems possible to reconcile the uniformity of the ironstones with the probability that their formation is partly or wholly conditioned by bacteria."

Thus, Lake-ore or Bog Iron-ore has by more than one writer been attributed directly to organic process, decomposition of vegetable matter and influence of bacteria, and has been discussed under this heading. In this book both are described in conjunction with other sedimentary ferruginous deposits in the category of chemically-formed rocks, for reasons above stated.

(B4) CARBONACEOUS DEPOSITS. This somewhat heterogeneous group comprises the naturally occurring solid hydrocarbons whose inherent variations and abundant transitional types render them difficult to bring within the limits of a few main

types. All agree, however, in fundamental biological origin, in which vegetable matter has played a significant part. The pure petrology of these rocks has been conspicuously neglected, save in one or two instances referred to in the sequel. They are none the less all susceptible to petrographical analysis along precise lines of investigation, though much depends on the production of the necessary thin sections, notoriously difficult to achieve in many of the types, *e.g.*, coals, asphalts.

No attempt is made here to consider every possible carbonaceous rock met with in the technology; such would be considerably beyond the scope of this volume. Nor is the fact lost sight of that, in the case of the coals and allied rocks, ultimate structural analysis rests largely on competent palæobotanical knowledge, again outside the province of this book. On the other hand, carbonaceous rocks have a very definite petrology, at once significant as a study of their mineral composition and of certain factors concerning their genesis. Recent tendencies have shown a desire existing among many geologists to bring such petrology up-to-date, and it is hoped that what follows in this connexion will help to clear the ground for further research. The attention of the reader is also drawn to relevant paragraphs on coal petrology (mainly detrital constituents) in Chapter III, pp. 68-70.

The following subdivisions of the carbonaceous rocks may be made as a provisional basis of discussion:—

- (B4. 1) Peat (p. 328).
- (B4. 2) Lignite (p. 329).
- (B4. 3) Coal and Anthracite (p. 330).
- (B4. 4) Cannel and Torbanite (p. 334).

(B4. 5) Oil Shale (p. 336).

(B4. 6) Asphalt and Asphaltic Impregnations (p. 337).

(B4. 1) **PEAT.**

Lith. Partially carbonised vegetable matter in which much of the latter is still recognizable in the form of plant roots, stems, fibres, etc. There is often, however, a fine, earthy, clay-like matrix, very homogeneous in character and only decipherable under the microscope. Colour varies from dark brown to black, while texture (*q.v.*) and degree of consolidation are very variable. A certain amount of mineral-matter in the form of sand is often visible to the naked eye. Hill or "upland" peat, as it is termed, differs in outward characters from fen-peat, the latter being essentially swamp-muck. Upland peat is more fibrous and spongy and contains much *sphagnum* and other mosses, while tree-trunks and branches may be embedded in it. Fen-peat is more homogeneous, darker in colour, and is composed largely of amphibious swamp-plants, *e.g.*, sedge, rushes, etc. A very crude "stratification" is sometimes apparent in large samples.

Text. Coarse, fibrous, earthy; often compact and clay-like.

Shape. Mineral particles A.

Min. Comp. Mineral particles are chiefly quartz, iron-ores, and the more stable accessory species common to neighbouring rocks. In the most compact types, inorganic matter may be less than 3 per cent.

Mech. Comp. Grade-size of mineral particles variable, but often of the sand-grade.

Micro. Peat varies microscopically according to the depth below the uppermost layers from which samples are taken. The superficial material is incoherent when dry, and any inorganic matter is easily washed out with water. The rest consists of modern plant material, much fibrous tissue, rootlets, etc. With greater depth, samples become more compact and change in character, incipient carbonisation also being apparent. Relieved of its water, this material is made up largely of a blackish-brown, inert, clay-like substance (humus), a restricted amount of plant-remains, and "sand," recognizable from scattered quartz grains

(by polarised light). For the most part this form of peat is structureless, the ingredients lying haphazardly, except in the lowest layers, when some degree of parallelism (bedding) may be observed. The inorganic matter is best studied by segregating it from the mass of the rock (p. 68).

Types. Upland peat from the Pennine Hills, England, and from the Grampians, Scotland; Lowland or Fenland peat from Cambridgeshire, etc.¹

Ref. ¹ E. A. N. Arber, *The Natural History of Coal*, 1912, ch. iv., and refs. cited.

General References.

F. W. Clarke, *Data of Geochemistry*, U.S.G.S., Bull. 770, 1924, p. 760 and refs. cited.

G. W. Tyrrell, *Principles of Petrology*, 1926, p. 243.

(B₄. 2) **LIGNITE.**

[Fig. 118, Pl. xxx.]

Lith. This term covers a number of different substances which, in so far as carbonisation is concerned, fall midway between peat and coal (bituminous). Examples are lignite proper, brown coal, pitch and glance coal, jet, etc. Such rocks occur in the geologically younger deposits, chiefly Mesozoic and Tertiary, in contradistinction to the bituminous coals of Palæozoic age. The rock is normally compact, with a dull black or brown lustre, these also being the characteristic colours. Composition and external features vary widely. In thin seams it is often intersected with fine vertical or oblique cracks, and splinters readily. More massive material breaks with conchoidal fracture. Plant remains seldom recognizable megascopically. Clusters and aggregates of pyrite common.

Text. Uniform, fine, smooth; in some varieties earthy.

Shape. Mineral particles usually A.

Min. Comp. Quartz, iron-ores (especially pyrite), zircon and other occasional accessories. In some of the Bovey Tracey lignites (Devonshire) detrital minerals derived from the Dartmoor granite and associated rocks have been isolated.

Mech. Comp. Mineral particles variable, but on the whole of fine (silt) grade.

Micro. Thin sections of lignite exhibit much brown, translucent matter for the most part optically inert, though faint birefringent reaction in patches is some-

times discernible. Traces of vegetable structure are frequently noted. Pyrite, and limonite staining are common features. The average section tends to be thick and opaque in the centre, though the edges are frequently very thin and this facilitates observations. Gypsum and calcite have both been observed in these rocks. In many examples there is noted a rough parallelism, sometimes distinct lamination, of the chief organic ingredients. The presence of veins and pockets filled with secondary mineral is not uncommon. The inorganic matter is best studied separately as a segregation from the main mass of the rock, by digesting it with suitable solvent (p. 68).

Types. Upper Lias, Whitby, Yorkshire, "Jet," homogeneous, coal-black substance, with resinous lustre and conchoidal fracture, often showing coniferous wood structures under the microscope;¹ Wealden (Wadhurst Clay), Sussex, lignite seams with pyrite, calcite; Fairlight Clay, lignite associated with siderite, etc.; Upper Oligocene, Bovey Tracey, Devonshire, typical lignite with *sequoia* wood, fronds of *Osmunda lignitum*, leaves and seeds of various plants, and conspicuous mineral matter.²

Ref. ¹ *Mem. Geol. Surv., Spec. Rep. Min. Resources, Gt. Brit.*, vii., 1918, pp. 22-23.

² *Op. cit.*, pp. 1-18; also A. J. Jukes-Browne, *Stratigraphical Geology*, 1912, p. 578.

General References.

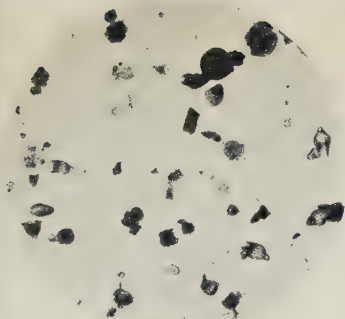
E. A. N. Arber, *Natural History of Coal*, 1912, pp. 60-61, 65, 122.

F. W. Clarke, *Data of Geochemistry*, U.S.G.S., Bull. 770, 1924, p. 763, and refs. cited.

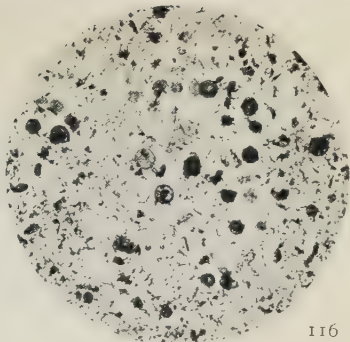
(B₄. 3) **COAL AND ANTHRACITE.**

[Figs. 119-20, Pl. xxx, & Fig. 122.

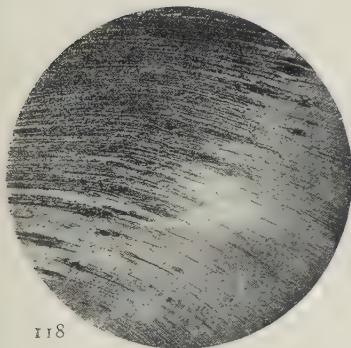
Lith. Under this heading are considered the so-called bituminous coals and anthracite. Both imply, for the most part, considerable geological age (Palæozoic) for their achievement. In composition and degree of carbonisation, coal may be said to lie between lignite on the one hand and anthracite on the other; but the term cannot be sharply defined, as some coals decidedly "overlap" the lignite types, while transitions to anthracite are common. Anthracite is essentially a variety of coal containing less than 10



115



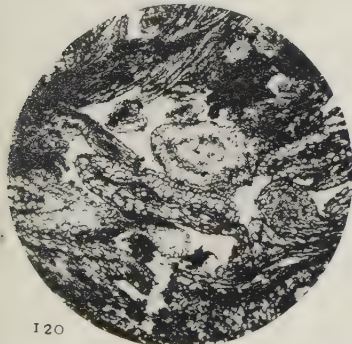
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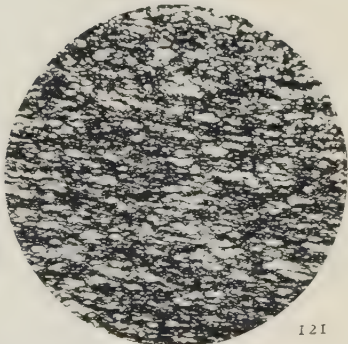
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121

ABYSSAL OOZE, LIGNITE AND COAL.

- FIG. 115. Radiolarian Ooze, S. Pacific, 2,425 fms. [x 25.]
 „ 116. Diatomaceous Ooze, Indian Ocean, 1,950 fathoms. [x 45.]
 „ 118. Lignite (Oligocene), Bovey Tracey, Devon. [x 14.]
 „ 119. Spore Coal (Coal Measures), Moira Colliery, Leicestershire.
 [x 25.]
 „ 120. Halifax Hard Coal (Lanarkian), Deighton, Yorks., with
Lyginopteris oldhamia. [x 15.]
 „ 121. Torbanite, Moifontein District, S. Africa. [x 14.]

per cent. of volatile matter and over 90 per cent. of carbon. Lithologically, bituminous (or humic) coal presents the appearance of a well stratified, carbonised mass of vegetable matter, some of it discernible as such, much of it compact, homogeneous and void of megascopic structure. Bedding may be thin or thick; sometimes exceedingly fine laminæ are developed. Both texture and lustre are notable, alternating dull and bright bands being characteristic. Coal is always

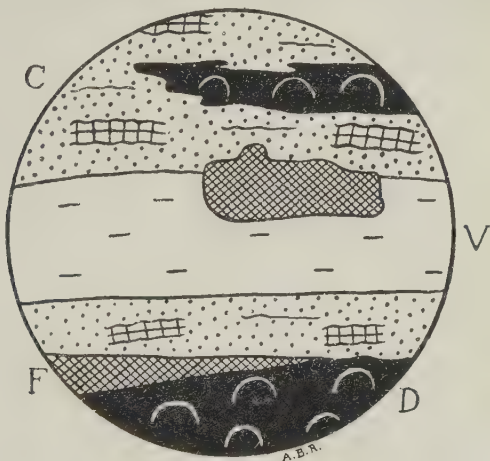


FIG. 122. Coal Constituents: c, clarain; d, durain; f, fusain; v, vitrain. (After M. C. Stopes, *Proc. Roy. Soc. London*, B, xc, 1917-19, p. 483.)

well jointed, yielding roughly rectangular blocks. The presence of pyrite along the bedding planes, on joint-surfaces or in pockets, is common. Anthracite is much harder than ordinary coal, has a somewhat metallic lustre, does not soil the hands, and breaks with an irregular, conchoidal fracture.

Considerable difference of opinion exists regarding the nature of the materials composing the coal-substance. As some of these are given particular names and can be recognized megascopically, they may conveniently be mentioned here, though to some extent

this anticipates remarks under "microscopical observations." The "*Fusain*" component is the soft, powdery, charcoal-like material detected along some of the bedding planes. In contrast to this is the compact "*Bright Coal*" and "*Dull or Matt Coal*"; to the latter M. C. Stopes has given the name "*Durain*."¹ The bright coal (sometimes known as "*Glance Coal*") much resembles jet. The dull coal is grey-black, lustreless and rough. There are, further, two varieties of bright coal, "*Clarain*" and "*Vitrain*"; the former exhibits smooth surface and glossy lustre, with fine lamination; it also shows intercalations of durain. Vitrain, on the other hand, is homogeneous, with brilliant lustre, conchoidal fracture, presenting clean-cut boundaries to the associated substances; it is supposed to represent "hardened colloidal carbonaceous jelly resulting from complete decomposition of plant matter."²

C. S. Fox has recently had occasion to examine these coal substances in really thin sections under the microscope, and has reached certain conclusions which differ in fundamental respects from the views just summarized.³ These are more appropriately discussed below.

Text. Variable; fine and compact, to coarse, powdery, earthy in coal; fine, smooth, resinous in anthracite.

Shape. Mineral particles A. Isolated particles of coal-substance also A.

Min. Comp. Al. Quartz, tourmaline, garnet, zircon, rutile, metallic ores, etc.; more rarely sulphides and native elements (p. 69).

Au. Calcite, siderite, pyrite, limonite, silica, ankerite,⁴ etc., in addition to the various forms of carbonaceous matter.

Mech. Comp. Detrital constituents usually of fine grade.

Micro. The essential factor to the study of coal, of whatever kind, is a really thin, translucent, if not transparent, section; this requires considerable skill to prepare and, in point of fact, the best sections available have so far been produced by one laboratory whose method has not been divulged. C. S. Fox, working on slides from

¹ *Proc. Roy. Soc. London*, B., 90, 1919, pp. 470-87.

² G. W. Tyrrell, *Principles of Petrology*, 1926, p. 245.

³ *Mining Mag.*, xxxvi., 1927, p. 16.

⁴ T. Crook, *Mineralogical Mag.*, xvi., 1912, p. 219.

this laboratory, has examined the so-called substances clarain, vitrain, durain and fusain derived from certain British coals (both in parallel and transverse sections), and writes as follows:—¹ “ Except for the slides of so-called fusain, which obviously contain much inorganic matter—pyrite, calcite and siderite—as well as what appears to be free carbon, the matrix, where thin enough to be translucent, is composed of the madder-red substance. In the sections cut vertical to the laminæ this substance shows very faint pleochroism in plane polarised light and decided straight extinction between crossed nicols, and again behaves as though the whole were part of a single crystal.” He also found in all the slides sections of the resinous wall of spores of red or gold colour, with bright, gold, translucent microspores packed in along the laminæ. He further says, “ In all the slides cut parallel to the bedding the translucent madder-red material behaves as an isotropic substance in polarised light . . . (with) a doubtful approach to a uniaxial figure.” He believes that the madder-red material is the same in all slides examined and concludes that “ There is no doubt whatsoever that the substance called vitrain is the same as clarain.” “ In short, the coal constituents are: (a) Vitro-clarain or pure bright coal as the chief component; (b) sporangia cases and spores and other resinous bodies as modifying constituents; (c) mineral charcoal or fusain as a peculiar subsidiary constituent, evidently marking a ‘ break ’ in the normal process of coal accumulation; and (d) the primary inorganic matter of the original plant as well as the secondary inorganic material which has been deposited in the coal, in joints and cracks and other channels for infiltrating waters.” Every student of coal, whether from a palæobotanical or petrological standpoint, should carefully read this paper. The author’s observations serve to confirm much of what that investigator has stated. Fox does not, however, touch on the detrital constituents of these rocks, which are no less interesting and significant; for methods of study, see p. 68. Finally, the work of A. Stuart may be quoted on South Welsh anthracite, who “ has been

¹ *Op. cit.*, pp. 20-22 See also H. B. Milner, *Mining Mag.*, xxxvi., 1927, p. 93.

able to distinguish bright bands of splendid lustre and structureless character, corresponding to vitrain; black bands of fairly bright coal with waxy lustre, and dark black 'charcoal' bands, representing fusain."¹

Types. Palæozoic, Coal Measures, Warwickshire, Lancashire and Yorkshire coalfields, etc., etc.;² anthracite from South Wales, etc.³ (N.B.—C. S. Fox's slides were of coal from Exhall, Warwickshire, and from the Trencherbone coal, Atherton, Lancashire).

Ref. ¹ *Geol. Mag.*, lxi., 1924, pp. 360-6, quoted from G. W. Tyrrell, *op. cit.*, p. 247.

² A. J. Jukes-Browne, *Stratigraphical Geology*, 1912, pp. 294-99.

³ A. Stuart, *op. cit.*

General References.

E. A. N. Arber, *Natural History of Coal*, 1912.

D. White & R. Thiessen, *The Origin of Coal*, U.S. Bureau of Mines, 38, 1913.

M. C. Stopes & R. V. Wheeler, *Monograph on the Constitution of Coal*, Dept. Sci. and Indust. Research, London, 1918.

F. W. Clarke, *Data of Geochemistry*, U.S.G.S., Bull. 770, 1924, pp. 768-775, and refs. cited.

R. Potonié, *Einführung in die allgemeine Kohlenpetrographie*, Berlin, 1924.

R. Thiessen, *Journ. Geol.*, xxviii., 1920, pp. 185-209. (See also paper by C. S. Fox (above) for review of literature dealing with microscopy of coal).

(B4. 4) **CANNEL AND TORBANITE.** [Fig. 121, Pl. xxx.

Lith. The distinction between cannel and torbanite on the one hand, and between torbanite and oil shale (B4. 5) on the other, is by no means an easy one to make; practically every gradation exists between them. The essential property of cannel is its dull, lustreless character, conchoidal fracture and ability to burn readily with a bright flame, since it contains considerable amounts of volatile matter. Torbanite is similar in external appearance; it also contains a high percentage of volatile matter, but is characterized by peculiar spore or algal structures (see below). Both cannel and torbanite (to which latter the name "bog-head" is often given) contain considerable mineral

matter; when this exceeds the carbonaceous matter, the rock automatically passes into the category of oil shale. Torbanite is considered to be an oil shale by some authors.¹ Bedding may or may not be apparent in these types; usually, if developed at all, it is on a large scale. Jointing is common and both tend to break into roughly rectangular blocks.

Text. Both cannel and torbanite are close-grained, fine, compact and homogeneous; the former often has a pitch-like texture, the latter is somewhat resinous.

Min. Comp. Little is known as to the nature of the mineral components of these rocks; detrital minerals are few and uninteresting in samples examined by the author. The coal-substance has been regarded by Potonié as "*sapropel*," a solidified jelly-like carbonaceous slime.

Micro. Under the microscope, slides of cannel and torbanite exhibit beautiful vegetable structures, differing considerably from bituminous coals, but showing affinities with the richer types of oil shale. Thin sections of cannel exhibit a number of plant-spores set haphazardly in a translucent, more or less optically inert, structureless mass. Torbanite contains an abundance of yellow, oval bodies considered to be spores by some authorities, *algæ* by others. Cannel is stated to be composed largely of the spores of *Lycopods*; torbanite, of gelatinous *algæ* known as *Pila* and *Reinshia*; actually the true nature of these organic remains is the subject of considerable controversy. For the rest, both coals indicate the presence of inorganic matter, e.g., calcite, pyrite, limonite, quartz, but the substances characteristic of bituminous coals seem to be absent, indicating a totally different origin for cannel and torbanite, or at least a different mother-substance; on this most investigators are agreed, but more research is required before these types can be said to be defined petrologically.

Types. Cannel from the Coal Measures of North Staffordshire, Yorkshire, Flintshire, etc.;² Boghead or Torbanite from Torbane Hill, Scotland ("Torbane Hill Mineral, West Lothian");³ "Tasmanite," Tasmania, "spore coal."⁴

Ref. ¹ A. Holmes, *Nomenclature of Petrology*, 1920, p. 227.

² *Mem. Geol. Surv., Spec. Rep. Min. Resources, Gt. Brit.*, vii., 1918, p. 46.

- ³ *Mem. Geol. Surv. Oil Shales of the Lothians*, 2nd ed., 1912, p. 159; 3rd ed., 1927, pp. 1, 242, etc.; H. R. J. Conacher, *Trans. Geol. Soc. Glasgow*, xvi., 1917, p. 164.

- ⁴ R. Potonié, *op. cit. infra.*, pp. 28-33.

General References.

- R. Potonié, *Allgemeine Petrographie der "Olschiefer" und ihrer Verwandten*, Berlin, 1928.
E. A. N. Arber, *Natural History of Coal*, 1912.

(B4. 5) **OIL SHALE.** [Figs. 123-28, Pl. xxxi.]

Lith. Oil shale, if the exceedingly rich types approximating cannel and torbanite be excluded, normally combines the essentials of ordinary sedimentary shale plus a varying amount of carbonaceous matter which, on destructive distillation, yields a form of petroleum. It differs considerably in megascopic characters from either cannel or torbanite. Usually black, brown or greyish-brown in colour; distinct lamination, often finely developed. Many varieties have a leathery appearance and when cut with a knife peel in the form of curved flakes, which may burn with a luminous flame.

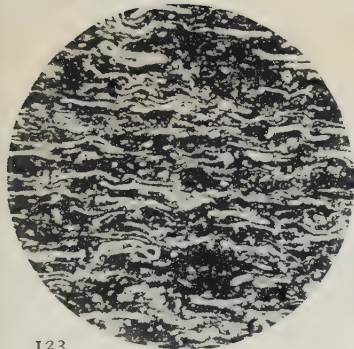
Text. Fine, smooth, often polished; some varieties resinous.

Shape. Detrital particles A to SA.

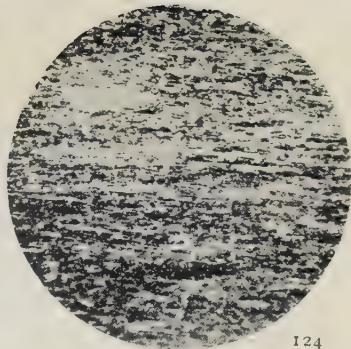
Min. Comp. *Al.* As for shale (A3. 9, p. 300).

Au. Carbonaceous matter of distinctive character (see below) in addition to carbonate of lime, silica, limonite and clay-substance. Part of the carbonaceous matter from which oil is distilled is known as "kerogen."

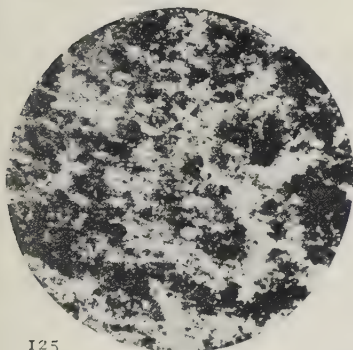
Micro. Oil shale should be studied petrologically in the same way as ordinary shale, i.e. by parallel and transverse sections. Under the microscope the essentially laminated feature is seldom in doubt, while quartz, iron-ores and secondary minerals such as limonite and calcite, also pyrite, are easily diagnosed. The organic matter, however, presents a more difficult problem. According to some observers there are four distinct types of material: the "ulmic" binder or ground-mass, spore and pollen exines, cuticles and cuticular secretions, and *algæ*; the latter approximate similar bodies found in spore coals (B4. 4). With approach to cannel or boghead types, the organic matter becomes more pronounced and includes fronds,



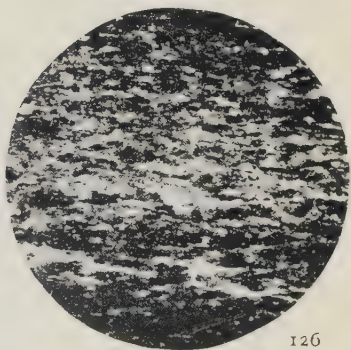
123



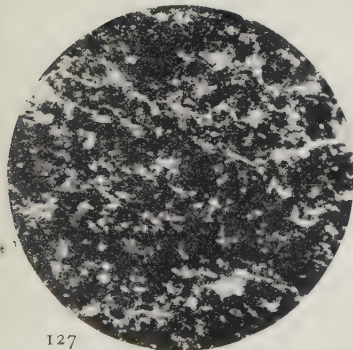
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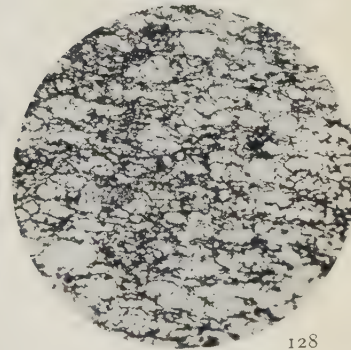
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126



127



128

OIL-SHALE.

- FIG. 123. "Tasmanite," Tasmania. [x 25.]
 ,, 124. Oil-shale (Carboniferous), Oakbank, Linlithgow, N.B. [x 25.]
 ,, 125. do. (Kimmeridgian), Kimmeridge, Dorset, || bedding. [x 15.]
 ,, 126. do. do. do. do. || bedding [x 15.]
 ,, 127. "Kuggersite" (Ordovician), Esthonia. [x 40.]
 ,, 128. Oil-shale, Blue Mountains, New Zealand. [x 22.]

To face page 336.

PLATE XXXI.

filaments of *algæ*, *fungi* fragments, etc. Some measure of parallel orientation of the organic material is observed in these shales, but the inorganic impurities are on the whole irregularly distributed. In some varieties, crystalline calcite occurs as secondary infillings of plant spores or replacing algal structures.

Types. Oil shale from the Lothians, Scotland, type material;¹ Kimmeridge oil shale, Dorset, a variable type with calcite, pyrite and a distinctive pyritised crinoid, *Saccocoma*, visible to the naked eye on bedding planes;² Tertiary oil shale from Green River, Utah, with crustacean material, cuticular spores and resins.³

Ref. ¹ *Oil Shales of the Lothians*, *Mem. Geol. Surv.*, 2nd ed., 1912, and 3rd ed., 1927; H. R. J. Conacher, *Trans. Geol. Soc., Glasgow*, xv., 1917, p. 161.

² *Mem. Geol. Surv., Spec. Rep. Min. Resources*, *Gt. Brit.*, vii., 1918. (For significance of *Saccocoma*, see *Geol. Surv., Gt. Brit., Summary of Progress*, 1910, p. 62, etc.).

³ W. H. Twenhofel, *Treatise on Sedimentation*, 1926, p. 297 & refs. cited; also fig. 32.

General References.

T. Stadnichenko & D. White, *Bull. Amer. Assoc. Pet. Geol.*, x., 1926, p. 860.

R. Potonié, *Allgemeine Petrographie der "Olschiefer" und ihrer Verwandten*, Berlin, 1928.

(B4. c) ASPHALT AND ASPHALTIC IMPREGNATIONS.

[Fig. 129, & Figs. 130-35, Pl. xxxii.]

Lith. In this category are placed those peculiar forms of solid hydrocarbon ranging from the purest bitumen deposit, to rocks in which only a comparatively small percentage of asphalt occurs as impregnating material. While this course may be conveniently adopted as a basis of petrological description, from chemical and physical standpoints the materials vary widely and can hardly be said to come under any one heading. It will further be obvious that, in the case of low percentage impregnation-types, the rocks constitute hybrids of mechanically- and organically-formed deposits, which might at first glance seem to justify their segregation from the purely carbonaceous deposits; but with types in which the organic material may vary from 5 to 97 per cent., it is difficult to draw any sharp

line of division, and as the majority is indeed highly carbonaceous, there is little reason for defining a separate hybrid group. At the outset it should be noted that the term "bitumen" is really a group-name to include most of the naturally occurring hydrocarbons, of which "asphalt" is the solid or semi-solid manifestation; "bitumen" is, however, often used loosely to designate all forms of solid asphalt, etc.

Megascopically pure asphalt is characterized by a black colour, glossy appearance, definite fracture and brittle tendencies; with the approach to semi-solid forms, fracture and brittle tendencies are obliterated, also the colour often changes to shades of dark brown; where the asphalt occurs as an impregnation, *e.g.*, in limestones or sandstones, it tends to be very finely disseminated and to play much the same rôle as an infiltrating mineral solution.

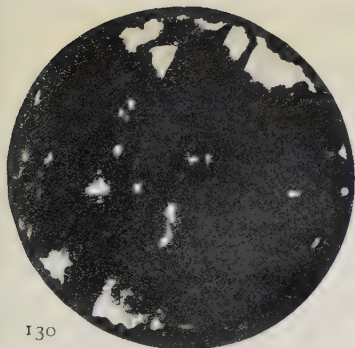
The following different types of these rocks may be recognized:—native asphalt, containing less than 10 per cent. of mineral matter; native asphalt occurring in all proportions as impregnating material or sediments; so-called "asphaltites" which include gilsonite, glance pitch and grahamite (the "manjak" of Barbados belongs here); and asphaltic pyrobitumens, including albertite, elaterite, etc., which, with increasing mineral matter, pass into asphaltic shales, finally bridging the gap between asphalt as such and oil shales.

Text. Mineral particles when excessive may produce a gritty texture, but in the purest forms asphalt is very smooth, homogeneous and pitch-like.

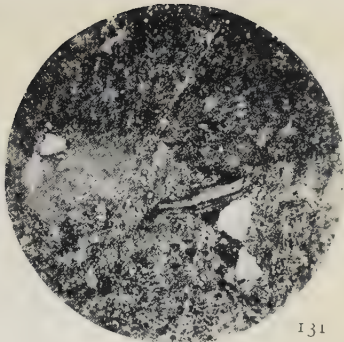
Shape. Detrital particles A to SA.

Min. Comp. Excluding the impregnation-types, the only minerals discernible under the microscope are the normal, stable detrital species. The hydrocarbon behaves as a dense, complex matrix, void of any crystalline properties.

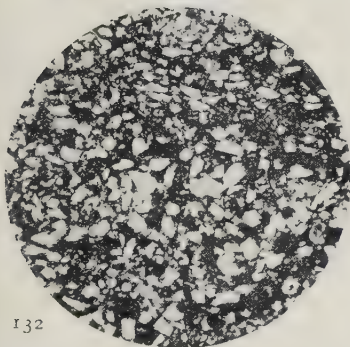
Micro. The method of studying these rocks depends largely on their nature, purity and degree of solidification. Where it is possible to cut thin sections, these should always be employed; this applies to solid native asphalts and asphaltites, equally to all impregnated rocks. Detrital minerals are best investigated as concentrates segregated by dissolving out the hydrocarbon



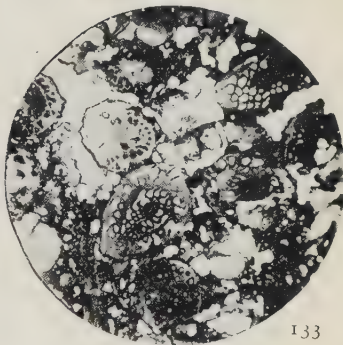
130



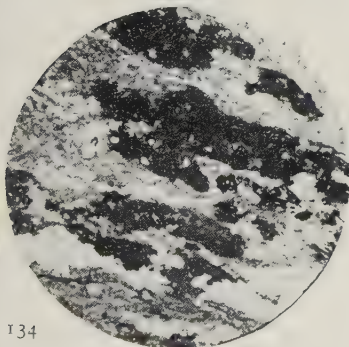
131



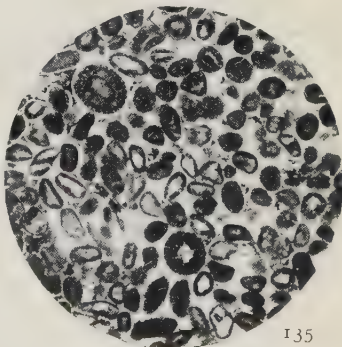
132



133



134



135

ASPHALT AND IMPREGNATED ROCKS.

- FIG. 130. Asphalt, "Pitch Lake," Trinidad. [x 48.]
 ,, 131. do. Roumania. [x 15.]
 ,, 132. Impregnated Sandstone, P  chelbronn, Alsace. [x 23.]
 ,, 133. do. *Fusulina* Limestone, Syzran, Simbirsk, Russia.
 [x 11.]
 ,, 134. Impregnated Limestone, Dept. of Gard, France. [x 15.]
 ,, 135. do. Oolitic Limestone, Hanover. [x 25.]

(p. 70). [N.B.—In the preparation of the thin section, the greatest care must be taken to avoid heating the material sufficiently to cause it to flux with the mountant, or otherwise to develop artificial structure.] Under the microscope asphalt exhibits a brown translucency where sufficiently thin; but few optical reactions can be obtained, nor in most cases can any structure in the hydrocarbon be made out. Where mineral matter is present, the quartz grains are easily picked out by polarised light; sometimes incident light observations aid the discrimination of organic and inorganic matter. Many examples of asphalt which, from megascopic observation, seem remarkably pure, are found to contain abundant quartz and other minerals on closer analysis. The most interesting and profitable research, however, is that on the impregnated rocks where, given a skilfully prepared section, the manner and degree of impregnation of a normal sedimentary rock can be studied. In these cases much depends on the rock itself. With sandstones, the asphaltic material is seen to act very much in the nature of a cement, filling voids and mineral-interstices, or where bedding is manifest, “pushing” its way along the planes, often disrupting the normal relationship of the quartz particles. Sometimes a definite linear distribution of the asphalt is noted, in other examples, especially in fine-grained sandstones and siltstones, it more or less saturates the rock. Porosity plays an important part, and where this is seen to vary, producing a “tight” sand, impregnation often stops abruptly. Impoverishment of the hydrocarbon causes it to appear in patches throughout the rock. In limestones the manner of impregnation is largely determined by the nature of the organic components and the degree of crystallization of the matrix. Often the fossil shells are sufficiently filled with mineral matter to avoid further contamination by the hydrocarbon, which is thus forced to confine itself to the matrix or to voids; on the other hand, where mineral infilling of shells or chambers is loose, or where cracks have been developed through which material can penetrate, asphalt may be seen to fill not only the interiors, but often fractures and cracks in the shells and even in calcite crystals. Where fine-grained calcareo-argillaceous rocks are involved, *e.g.*,

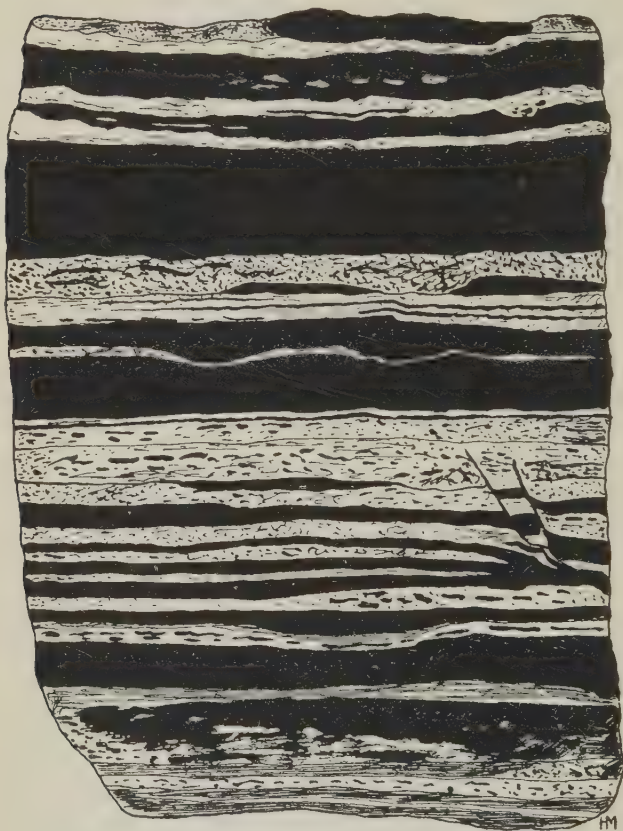


FIG. 129. Impregnated (Asphaltic) Limestone
Dept. of Gard, France ($\frac{1}{2}$ nat. size).

marl, the "patterning" of the asphaltic material is very characteristic, due to the irregular porosity and permeability of the rock towards the hydrocarbon. In these cases it will often adhere to those planes or parts of the marl in which some degree of secondary crystallization of the calcareous mud is apparent; where, however, it has been able to saturate the rock-particles, the whole specimen shows discoloration, and high power magnification reveals thin films of asphalt coating the constituent particles. With excess of the carbonaceous matter, beds of asphalt tend to alternate with non-impregnated rock, and a definitely banded structure is seen. The existence of jointing in such rocks determines the "leakage" of asphalt from one layer to another and sometimes the spread of detrital grains which are thus locally transported: this phenomenon constitutes a very pretty study under the microscope.

Types. Asphalt from the Bermudez "Pitch Lake," Venezuela, with just over 3% mineral matter; asphalt from the "Pitch Lake," Trinidad, B.W.I., with varying mineral matter; Glance Pitch or "Manjak" from Barbados; asphaltic impregnated sandstone, P  chelbronn, Alsace; asphaltic impregnated limestone, Val de Travers, W. of Neuchatel Lake, Switzerland, varying from 10 to 17.5% impregnation; asphalt impregnation of limestone, marl, sandstone and shale, Department of Gard, France, between 5 and 16%.¹

Ref. ¹ H. Abraham, *Asphalts and Allied Substances*, 1918, chs. viii., ix. and x.

General References.

G. H. Eldridge, *U.S.G.S., 22nd Ann. Rep.*, pt. i., 1901, p. 222.

S. C. Ells, *Bituminous Sands of Northern Alberta*, Canada, Dept. of Mines, Bull. 632, 1926.

(B5) PHOSPHATIC DEPOSITS. These comprise the phosphatic rocks of organic origin as distinct from mineral apatite deposits, and although sporadically developed on a large scale in different parts of the world, they are comparatively unimportant as petrological studies. The group includes phosphorite, the primary or metasomatic

form of phosphate (hydro- or fluo-calcium carbonophosphate); guano, a friable or earthy type derived from the excrement of sea-birds, etc.; the coprolites or fossil excreta of fishes, reptiles and mammals. Closely allied are the bone-breccias of similar composition. Many local varieties of these deposits are known. For present purposes it is unnecessary to split this group up into separate types, and the following general description will suffice (*Figs. 136-137, Pl. xxxiii*).

Lith. Primary, bedded phosphate deposits, *e.g.*, phosphorite, vary considerably in external characters. The pure types are grey, brown or black, the latter usually implying presence of hydrocarbon. Recognizable organic remains may or may not be in evidence: these vary from shell-fragments to bones and fish remains, etc. Different structures prevail according to conditions of formation, and to some extent with locality; for instance, in the Nigerian deposits W. Russ has described granular, nodular, fine and coarse vesicular and compact types.¹ In some granular examples small, rounded pellets of an amorphous form, collophane (p. 260), may occur, giving the rock a pseudo-oolitic character. The nodular type "has a conglomeratic appearance derived from the ellipsoids and irregular cylindrical nodules of calcium phosphate."² The vesicular varieties are altered products into which enter phosphates of iron and alumina. Guano, coprolites and the "bone-phosphate" of the breccias are for the most part amorphous; guano is dry, pulverulent, earthy and friable (under arid conditions) and contains considerable impurity in the form of nitrate, lime carbonate, etc. Coprolites are grey, green or brownish-black in colour; in some cases they are phosphatised matter entirely, in other examples fossil-shell fragments are included. Various phosphatic nodules found in different strata may either be coprolites in the strict sense, or be composed of collophane, calcium carbonate and mineral matter.

¹ W. Russ, *Geol. Surv. Nigeria*, Bull. 7, 1924, p. 11.

² *Op. cit.*, p. 12.

Text. Phosphorite: fine, compact, homogeneous, to coarse, earthy vesicular (like pumice); guano is earthy, friable; nodules and coprolites are usually smooth, sometimes "soapy"; bone-phosphate is rough, powdery, or hard and compact, sometimes coated with secondary crystalline material.

Min. Comp. These phosphates are essentially varieties of calcium phosphate, with or without fluor, calcium carbonate, iron phosphate, aluminium phosphate, etc. Among specific minerals may be mentioned collophane, dahllite and francolite. Associated impurities include quartz, calcite, dolomite, chert, pyrite, marcasite, glauconite, etc.

Micro. These rocks are among the most variable materials to study microscopically; practically no two examples are alike. Except the rarer compact varieties of phosphate rock, most examples have the appearance of "conglomerates" in which the "pebbles" are rounded and of varying sizes, set in a matrix which is clear, turbid or iron-stained. For the most part, the larger constituents are phosphate grains, the matrix is a mixture of phosphate, aluminium phosphate, carbonaceous matter and detrital minerals. Fossil-shell and bone-fragments are common. Some of the phosphate is crystalline and gives definite optical reactions; for instance, in some types of granular, amorphous phosphate there is interstitial aluminous phosphate with bluish-grey aggregate birefringence. Much of this granular, amorphous material is probably collophane. Phosphatic nodules, coprolites, etc., are amorphous, but frequently some sort of nucleus is observed in thin section, *e.g.*, shell-fragment, bone, rarely inorganic matter. Phosphate casts of *foraminifera* and structural grains replacing those organisms are often observed. Various stages in phosphatic replacement of limestones occur. In bone-breccias in which phosphate prevails, both bone-fragments and matrix may be of lime phosphate, but usually some degree of secondary alteration is noted, with the production of iron phosphate, calcite and silica.

Types. Upper Cretaceous (Cambridge Greensand), Cambridgeshire, phosphatised fossils, phosphate nodules, etc.;¹ Lower Chalk, Cambridgeshire, etc., calcareo-phosphatic nodules of green colour, brown-yellow in-

side;² phosphate rock, Abeokuta Province, Nigeria, with iron and aluminium phosphates, etc.;³ guano deposits of Peru, Christmas Island (Indian Ocean), Navassa Island (Caribbean), etc.;⁴ Suffolk Box-stones.⁵

Ref. ¹ F. R. C. Reed, *Geology of Cambridgeshire*, 1897, pp. 100-103.

² *Ibid.*, p. 127.

³ W. Russ, *op. cit.* (N.B. This work contains some excellent photomicrographs of phosphate rocks).

⁴ W. H. Twenhofel, *Treatise on Sedimentation*, 1926, p. 400.

⁵ P. G. H. Boswell, *Geol. Mag.*, 1915, p. 253.

General References.

J. W. Gregory, *Trans. Geol. Soc. Glasgow*, xvi., 1917, pp. 115-163.

F. W. Clarke, *Data of Geochemistry*, U.S.G.S., Bull. 770, 1924, pp. 523-534.

L. Owen, *Phosphate Deposits of Ocean Island*, *Q.J.G.S.*, lxxix., 1923, pp. 1-15.

J. H. C. Martens, *Sand, etc., Florida*, *Florida State Geol. Surv.*, 19th Ann. Rep., 1928, pp. 33-123 (p. 43 for collophane).

A. L. du Toit, *Geol. Surv. S. Africa*, x., 1917.

O. Stutzer, *Zeit. f. Prakt. Geol.*, xix., 1911, p. 73.

A. Carnot, *Ann. des Mines*, x., 1896, pp. 137-251.

L. Cayeux, *Roches sedimentaires*, p. 235.

A. F. Hallimond, *Mem. Geol. Surv., Spec. Rep. Min. Resources, Gt. Brit.*, xxix., 1925, p. 35.

(C) CHEMICAL ORIGIN. This group comprises all inorganic deposits dependent for their formation on precipitation from solution, or on some definite chemical alteration of a pre-existing sedimentary rock, the latter process usually referred to as "metasomatic" change. On account of the obvious influence of organic agency in many geochemical reactions and the constant overlap between organically- and chemically-formed rocks in many instances, the present group is to some extent artificial. The example already

discussed (p. 325) is that of the ferruginous deposits, deliberately relegated to this chemical group notwithstanding the admitted influence of bacterial organisms in their formation.

On the other hand, the majority of rocks falling naturally into this category is clearly inorganic, *e.g.*, travertine, calc-sinter, gypsum, anhydrite, rock-salt, etc., and is a sufficient justification for retaining a division which shall include deposits of such definite chemical origin, and which further lends itself to internal rearrangement of types on the logical basis of chemical composition.

The real distinction between organic and chemical deposits lies in direct or indirect contribution; the former are primarily concerned with accumulation of actual organic substance; the latter may and often do imply organic agency or influence in their achievement, but their actual presence may not be manifest; in fact it rarely is so in these rocks.

The study of chemically-formed deposits is valuable from many points of view; their petrology (possibly "mineralogy" would be the more accurate term in most cases) is distinctive and interesting; their stratigraphical occurrences are always an inspiration of problems of genesis and relationship to their associated rocks; their significance in illustrating the principles of cementation of incoherent sediment — the authigenic factor — cannot be overlooked; while to petroleum geologists in particular, such materials as rock-salt, gypsum and anhydrite, are of vital importance in many oilfields.

For these and other reasons, chemically-formed deposits invite careful study and the same diligent use of the microscope as is accorded more complex rock-types.

Following the scheme of sub-classification adopted hitherto, the four main divisions are :—

- (C1) CALCAREOUS (p. 346).
- (C2) FERRUGINOUS (p. 349).
- (C3) SILICEOUS (p. 352).
- (C4) SALINE (p. 354).

(C1) CALCAREOUS DEPOSITS OF CHEMICAL ORIGIN. This division, relieved of those carbonate developments in which organic influence has clearly operated (dolomitic limestone, oolitic and pisolitic structures, group B), though chemical action in each case has undoubtedly taken place, may be said to be sufficiently distinctive. It includes such deposits as travertine or calc-sinter, stalactite and stalagmite growths, dolomite (in part). In connexion with the latter, much difference of opinion exists as to whether this substance can originate *per se* as a direct result of chemical precipitation from solution, many writers claiming the essential action of magnesia-secreting organisms as instrumental to its formation. The author agrees with those who maintain that the mineral can be generated independently from solution. For instance, dolomite occurs in association with rock-salt, gypsum, anhydrite, etc., in the Trias of Germany, in which development it does not in the least suggest replacement of an original limestone.

These deposits may be subdivided as follows :—

- (C1. 1) Calcium Carbonate : Calcite (p. 346).
- (C1. 2) Dolomite (in part) (p. 347).

(C1. 1) **CALCIUM CARBONATE: CALCITE.** (See also B1. 1, p. 307).

Lith. This subdivision includes the following variable examples:—travertine, calc-sinter, calc-tufa, stalactite and stalagmite growths; the first three are practically identical, consisting of accumulations of calcium carbonate possessing cellular, concretionary, compact, or earthy and porous tendencies. Stalactites are the pendent growths of calcium carbonate from the roofs of caves, etc., stalagmites the corresponding accumulations on the floors of such recesses. "Onyx Marble," a misnomer, is a well-banded variety of stalagmitic carbonate, and belongs here. In the case of travertine, etc., deposition is often quite irregular, producing encrustations and earthy accumulations rather than well organised structures, the characteristic of stalactites and stalagmites, where some development of concentric growth is always apparent when the specimen is split transversely. Colour varies from white, yellow to brown.

Text. Compact to earthy, friable.

Min. Comp. Essentially calcium carbonate, but often with impurities such as iron carbonate, limonite, silica, hydrocarbon, etc.

Micro. The crystalline nature of these rocks is seldom in doubt when tested under the microscope with polarised light. All the characteristic properties of calcite (p. 145) are observed, while the presence of impurities is easily detected. The concentric growth-layers of the stalactites, etc., are often picked out with impurity, e.g., limonite, while subsidiary radial structures may be observed. In the tufas, some proportion of the mineral is powdery and appears to be amorphous; usually no special structure is apparent unless encrustation about some particular nucleus has taken place uniformly.

Types. Carboniferous Limestone of Derbyshire, etc., for all these types of carbonate.

Ref. V. C. Allison, *Journ. Geol.*, xxxi., 1923, pp. 105-125.
W. H. Twenhofel, *Treatise on Sedimentation*, 1926, p. 247.

(CI. 2) **DOLOMITE** (in part). (See also BI. 2, p. 312.)

Lith. Dolomite occurring as the mineral (not as a partial replacement of limestone) and in intimate association with other inorganic deposits, is an interesting development. In its massive form it constitutes dolomite

rock, a white, grey, green, brown, sometimes pinkish, crudely stratified deposit, often with a somewhat pearly lustre. Brown staining is mainly due to ferrous carbonate, other prominent colouring may be due to manganese compounds. Usually dolomite is close-grained, uniform, and difficult to distinguish from limestone except by acid test; on the other hand, in veins or cavities (the latter very common in some examples), characteristic curvilinear crystals, resulting in "saddle-shaped" aggregates, may be observed, when the mineral is at once easily recognized.

Text. Medium, compact, sometimes friable.

Min. Comp. Essentially carbonate of calcium and magnesium, but with impurities of iron, sometimes manganese; often intimately associated with gypsum, barite, silica, more rarely celestite.

Micro. Under the microscope the simple rhombs of dolomite are, if developed, very characteristic; alternatively, somewhat rectangular forms as constituents of aggregates may be displayed. Where individual crystallization is obliterated by interferent mass-precipitation, a mosaic of irregular grains, almost indistinguishable from calcite, results; in such cases only a chemical test yields positive diagnosis (p. 146). In field-association with gypsum, anhydrite, rock-salt, etc., these minerals may be looked for in the slide, and are usually apparent to a greater or lesser extent, especially in joint-channels or cavities. A complete absence of organisms or organic structures is one of the differentiating features between dolomite and dolomitic limestone, though where the latter forms part of the series, separation of the two types is often an exceedingly difficult matter.

Types. Trias, Keuper Marls, Charnwood, Leicestershire, "quartzose dolomite," compact, granular, blue-grey crystalline rock composed of perfect rhombs of dolomite associated with quartz, aluminous silicate and barite;¹ other occurrences from the same formation show perfect rhombs of dolomite;² Raibl Beds, Tyrol, dolomite associated with gypsum.³

Ref. ¹ T. O. Bosworth, *Keuper Marls around Charnwood, Leicestershire*, *Leicester Lit. and Phil. Soc.*, pp. 54, 82, 84, 108.

² C. G. Cullis, *Rept. Brit. Assoc., for Adv. of Sci.*, Leicester, 1907, p. 506.

^a M. M. Ogilvie, *Q.J.G.S.*, xlix., 1893, p. 1.

General References.

Mem. Geol. Surv., Spec. Rep. Min. Resources, Gt. Brit., vi., 1918, p. 190.

F. M. Van Tuyl, *Iowa Geol. Surv.*, xxv., 1914, pp. 262-4.

F. W. Clarke, *Data of Geochemistry*, U.S.G.S., Bull. 770, 1924, p. 565 *et seq.*

(C2) FERRUGINOUS DEPOSITS. (See also B₃, p. 325.) Prevalent ideas with regard to the nature and origin of ferruginous deposits have been considerably clarified by the recent work of A. F. Hallimond on the bedded iron-ores of England and Wales, to which reference has already been made elsewhere.¹ Apart from the action of *bacteria* or *algæ* in instigating or influencing certain chemical reactions from which these rocks result, the essentially inorganic character of these deposits is now generally admitted, even to the extent of denying the probability of oolitic ironstones having been derived by metasomatic process from oolitic limestones. For present purposes it will suffice to recognize two contrasted occurrences.

(C2. 1) Bedded Iron-Ores (p. 349).

(C2. 2) Bog Iron-Ore (p. 352).

(C2. 1) **BEDDED IRON-ORES.** [Figs. 138-141, Pl. xxxiii. *Lith.* Hallimond divides the bedded iron-ores into two principal groups, the ferrous and the ferric ores; the former are the chamosite and chamosite-siderite mudstones, non-chamositic siderite mudstones, and siderite limestones; the latter include the ferric chamosite oolites, the limonite oolites, primary hæmatites and glauconite rocks. The mudstones correspond to the older terms "clay ironstone" or "blackband ironstone" of the text-books. Megascopically the chamosite and chamosite-siderite mudstones vary

¹ *Mem. Geol. Surv., Spec. Rept. Min. Resources, Gt. Brit.*, xxix., 1925.

greatly; the colour is green or brown; oolitic developments and compact mudstone alternating; organic remains and markings common. The siderite mudstones are on the whole darker in colour, of finer texture, nodular, or in thin beds; they resemble "cement-stones." Closely allied to them are the sphærosiderite rocks, in which spherulitic grains of the mineral are embedded in clay (p. 450). The sideritic limestones differ from the preceding types in consisting of aggregates of shell-fragments cemented with calcite and siderite. Of the ferric ores, the ferric chamosite oolites vary from black to red and brown oolitic and pisolitic mudstones, often highly magnetic, with conspicuous bedding and limonite cement; occasionally pyrite in nests. The limonite oolites are composed mainly of oolites of that mineral, not of chamosite as in previous types; they may be closely or sparsely packed, in the latter case the matrix of sandstone or mudstone is usually fine and homogeneous except where organic fragments are common; colour, grey, brown, reddish-brown. The primary hæmatites include turgite or hæmatite occurring as pebbly or nodular beds, or in brick-red massive varieties, etc. The glauconitic rocks include ironstones in which, as a result of weathering of sands containing that mineral in abundance, iron is concentrated mainly as limonite, though in some cases with a considerable amount of siderite; there is often a clay matrix, while the development of limonitic "boxstones" is characteristic; this material is in the nature of an "iron pan."

Text. Variable, from fine to medium grain in the mudstone facies, coarse to earthy in the oolitic developments.

Shape. Detrital particles SA.

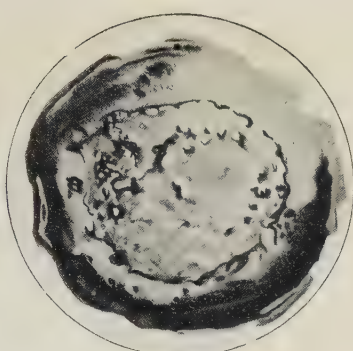
Min. Comp. Al. Quartz, iron-ores and miscellaneous accessory minerals.

Au. (including chemical precipitates), chamosite, siderite, dolomite, ferric oxide, magnetite, pyrite, glauconite, clay-substance, calcite, limonite, phosphates (collophane), etc.

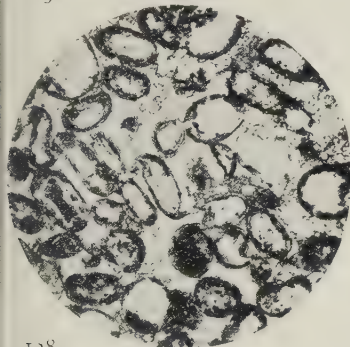
Mech. Comp. In the siderite mudstones, ooliths $1/60''$ in diameter; in average cases siderite crystals are about 0.02 mm. in diameter; detrital grains mainly of the silt grade.



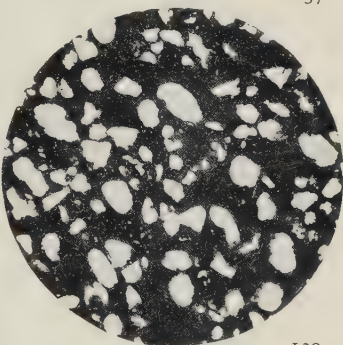
136



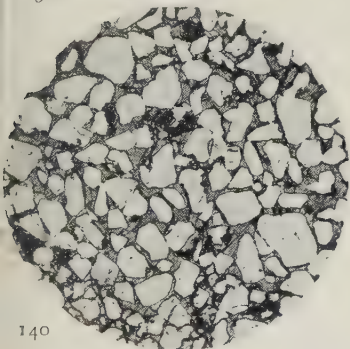
137



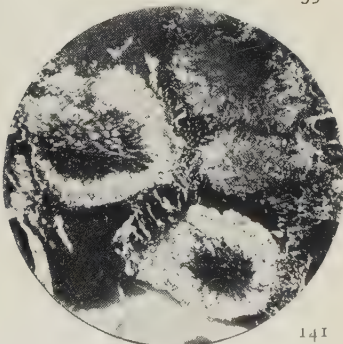
138



139



140



141

PHOSPHATES AND BEDDED IRON-ORES.

- 136. Calcium Phosphate Nodule, Oshosun, Nigeria. [x 50.]
- 137. Phosphate Rock, Oshosun, Nigeria. [x 5.]
- 138. Cleveland Ironstone (Liassic), Yorks. [x 23.]
- 139. Ironstone (Estuarine), Thrapston, Northants. [x 25.]
- 140. Abbotsbury Iron-Ore (Corallian), Abbotsbury, Dorset. [x 15.]
- 141. Pyritic Blackband (Coal Measures), Powell Duffryn, N. Wales [x 14.]

See page 350.

PLATE XXXIII.

Micro. In these rocks the ooliths are usually of chamosite, one of the chlorite minerals, and they may or may not contain siderite in rhombs or irregular grains. Siderite ooliths are much less common; these are set in a fine chamosite-mud ground-mass, often rich in siderite in rhombs or crystal-bunches. The chamosite ground-mass is green to brown in colour. Quartz, dolomite and accessory minerals are scattered throughout the rock. In the mudstones the ground-mass may consist of quartz, felspar, mica and clay-substance, with or without chamosite. A characteristic feature of many of the mudstones is the abundance of fossil-shell fragments often replaced by rhombs of siderite; other organic remains include fish-teeth, casts of boring worms, plant debris, etc. When sphærosiderite occurs, the spherulites are scattered in a clay-matrix; the former "are built up of long narrow fibrous crystals with straight extinction, radiating from the centre and often terminating in an irregular angular outline; sometimes the component crystals are fewer and broader. The ground-mass is generally of fireclay type, and is sometimes present in so small an amount that the spherules meet, forming polygonal cells. When quartz, etc., is present in the ground-mass, some of the coarser grains are often included in the spherules, an indication that these grew within the clay."¹ The sideritic limestones exhibit siderisation in all stages from cementing medium to complete replacement of calcite (metasomatism). In the limonite ooliths, the matrix consists of weakly birefringent clay-substance (? altered chamosite) with siderite, dolomite, quartz, etc.; the ooliths themselves are brown, translucent, and with radial-fibrous and concentric structure. Sometimes each grain is coated with an isotropic film of chamosite. In the glauconitic varieties, this mineral occurs conspicuously; the ooliths are of limonite showing concentric structure, set in a brown sideritic cement which also shows alteration to limonite.

Types. Middle Lias, Cleveland Ironstone, Yorkshire, example of chamosite mudstone and chamosite-siderite mudstone; also oolitic Cleveland Ironstone; Wealden, siderite mudstone, also sphærosiderite (Fairlight Clay, Sussex); Lower Cretaceous, Claxby Ironstone, Lincoln-

¹ A. F. Hallimond, *op. cit.*, p. 67.

shire, example of limonite oolite; Lower Greensand, Seend, Wiltshire, glauconitic ironstone with limonite boxes, etc.; Abbotsbury Iron-ore, Dorset, and Westbury Ironstone (Corallian), Wiltshire, both examples of limonite oolites.¹

Ref. ¹ A. F. Hallimond, *Mem. Geol. Surv., Spec. Rep. Min. Res., Gt. Brit.*, xxix., 1925. (N.B.—This work so far supersedes pre-existing accounts of these particular rocks as to render further references superfluous, though many will be found therein as footnotes where appropriate).

(C2. 2) **BOG IRON-ORE.***

Lith. In brittle flakes, thin beds, aggregates, or as filmy matter on water-surface; material usually soft, porous, and of brown colour. Clay is usually associated with the solid bog-ore, in fact often underlies it, and plant remains are common.

Text. Fine, smooth, to earthy and friable.

Min. Comp. Limonite, siderite, clay-substance, with (locally) iron silicate, iron sulphate, vivianite, "wad" or bog manganese, humus, etc.

Micro. In thin section, the solid iron-ore exhibits a brown to red colour, usually of fairly homogeneous material, much of which is optically inert, though easily studied by means of reflected light. Siderite when present is detected by its characteristic twinkling with the polariser. Vivianite is of comparatively rare occurrence and is suggested by bluish-green or dark blue prismatic crystals. Organic structures are very conspicuous, normally consisting of rootlets, twigs, leaves, sometimes seeds, frequently replaced by limonite.

Types. Various lacustrine and fluvial iron-ores and "iron pans"; Scotland, Sweden, etc.

General References.

N. S. Shaler, 10th *Ann. Rep., U.S.G.S.*, pt. i., 1890, p. 305.

R. Beck, quoted by W. H. Twenhofel, *Treatise on Sedimentation*, 1906, p. 327; also other refs. there cited.

(C3) **SILICEOUS DEPOSITS.** Included under this heading are those rocks owing their existence

* See also under *Limonite*, p. 206.

primarily to inorganic agency, *viz.*, precipitation from solution in which silica in one form or another is prevalent. Here belong siliceous sinter and, to a large extent, chert and flint. These latter, however, are concerned with recognizable organic remains contributory to their formation, more especially in the case of chert, and in the present state of our knowledge it seems desirable to discuss them under the heading of organically-formed rocks, though admittedly the claim of the chemical group is strong. This is another case of difficulty of classification raised by a genesis which contemplates more than one mode of origin. Accordingly chert and flint are described as types of group (B) (p. 320), leaving siliceous sinter as the example of the purely chemical siliceous deposit; even in this case it should be noted that organic agency has on more than one occasion been invoked to account for its formation.

(C3. 1) **SILICEOUS SINTER.**

Lith. This material is chiefly deposited as earthy encrustations in the vicinity of hot springs or geysers, hence the synonymous term "geyserite." It varies in colour from yellow to pink, green, brown, variation being noted with temperature at the time of formation. These colours have been attributed to gelatinous precipitation influenced by certain *algæ*, but the mechanism is not understood. Many examples resemble accumulated concretions, sometimes with a kind of "onion" structure, at other times having the appearance of "cauliflower" structure.

Text. Usually earthy, porous and friable.

Min. Comp. Amorphous silica, opal, with impurities of iron, manganese, etc.

Micro. Siliceous sinter examined under the microscope exhibits characteristic "growth" structure in ordinary transmitted light, but remains for the most part isotropic with polarised light. Few structures which can be termed even micro-organic are observed; certainly *algæ* are not conspicuous in the cold, consoli-

dated rock. Colouring matter is finely disseminated and is not attributable to any particular crystalline substance. Fibrous sinter is not uncommon, but individual fibres do not yield optical reactions.

Types. Yellowstone Park, U.S.A.; hot springs of Taupo, New Zealand; geysers of Iceland, etc.

General References.

W. H. Weed, *U.S.G.S., 9th Ann. Rep.*, 1889, pp. 613-676; also *Am. Journ. Sci.*, xxxvii., 1889, p. 351.

G. W. Tyrrell, *Principles of Petrology*, 1926, p. 223.

(C4) SALINE DEPOSITS. This group covers a variety of chemically-formed rocks characteristic of certain well-defined environments, *e.g.*, lagoons, inland lakes, relic (land-locked) seas, etc. It includes chlorides, sulphates, borates, nitrates, etc., occurring as products of precipitation usually in regular beds or layers, but lacking "stratification" in the accepted sense. Apart from such developments *per se*, certain of the compounds considered here also occur as replacements of pre-existing rocks, more particularly those of the calcareous group; the sulphates are implied in this connexion. Contrary to usual belief, microscopical examination of these sedimentary salts shows that they are among the most variable rocks found in nature, especially as regards structure; this may be of such a distinctive type as to characterize a particular development over a large area and through a limited thickness of deposit; thus careful study of structural features, particularly in regard to gypsum and anhydrite occurrences, is a matter of considerable moment in the identification of horizons in thick saline sequences. Such study is, however, much facilitated when chemical analyses of the rocks in question are available; these serve as a guide to the anticipation of closely allied products whose mineralogical characteristics may not be sufficiently obvious to aid their dif-

ferentiation from the chief constituents. The types chosen to illustrate this group are:—

(C4. 1) Chlorides (p. 355).

(C4. 2) Sulphates (p. 356).

(C4. 3) Nitrates and Borates (p. 359).

(C4. 1) **CHLORIDES.**

[Fig. 142, Pl. xxxiv.]

Lith. The chief examples of this group are rock-salt (halite) and sylvite (potassium chloride); the latter is comparatively rare. Rock-salt occurs either in recognizable crystal-form (halite) with marked cubic cleavage, in granular masses, or as thick, structureless, massive beds. In colour it varies from colourless to white, yellow, red, purple (with increasing impurity). Possesses a strong saline taste and readily dissolves in water. Many specimens exhibit considerable distortion. Sylvite is also a cubic mineral with strong cleavage, though seldom so conspicuous as in the case of rock-salt. It occurs as granular or massive developments, nearly always accompanied by impurities.

Text. Fine, glassy or "sugary."

Min. Comp. Halite (NaCl), with many impurities and associated salts, e.g., sulphates, carbonates, clay-substance, silica, etc. Sylvite (KCl), usually with halite, silicates, nitrates, etc.

Micro. Both rock-salt and sylvite are normally isotropic in polarised light, though some examples exhibit anomalous birefringence, probably due to impurities in most cases; strain-phenomena are possible. In ordinary transmitted white light the refractive index of rock-salt is less than Canada balsam, but by a small amount, so that the outlines of the crystals or sections of massive material are not prominent; with sylvite the R.I. is considerably less than that of balsam, with the result that a shagreened surface with bold outlines is characteristic. Colouring matter in both salts is noted as fine disseminations, seldom suggestive of recognizable minerals, except limonite. The cleavage is often well displayed where crystals are in evidence.

Types. Triassic salt deposits, Northwich, Cheshire; Presall, Lancashire; Staffordshire, etc.;¹ rock-salt and sylvite, Stassfurt, Germany.²

Ref. ¹ *Mem. Geol. Surv., Spec. Rep. Min. Res., Gt. Brit.*, xviii., *Rock-salt and Brine*, 1921.

² F. W. Clarke, *Data of Geochemistry*, U.S.G.S., Bull. 770, 1924, p. 222 *et seq.*

General Reference.

A. W. Grabau, *Principles of Salt Deposition*, 1920.

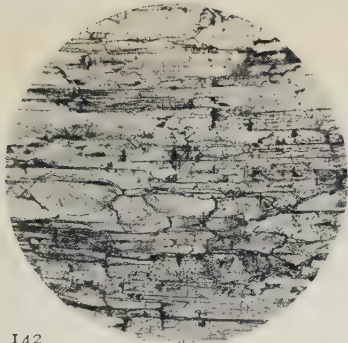
(C4. 2) **SULPHATES.**

[Figs. 143-47, Pl. xxxiv., & Figs. 148-152, Pl. xxxv.]

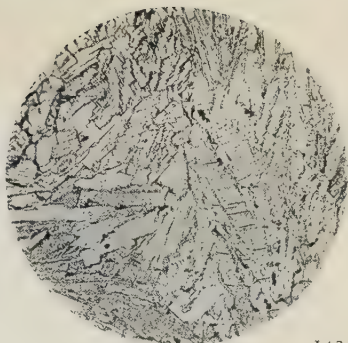
Lith. This group includes gypsum, anhydrite, barite and celestite as the commonest representatives of accumulated "salt" deposits. As individual minerals they have already received consideration in Ch. VI., to which further reference for mineralogical detail should be made. The following notes refer to their occurrence *en masse*. Gypsum normally occurs in massive aggregates of mutually interferent crystals, often decidedly fibrous, and with a saccharoidal structure. In colour it is white to pale pink, red or brown, the colouring matter being due to impurity, often to iron compounds or finely divided rock-flour.

Anhydrite also occurs massive, sometimes with distinct fibrous development; crystallization may be very coarse, due to the packing together of crudely rectangular prismatic crystals. The structure is of a schistose character in some examples. Colour white, grey, blue or red. It is much harder than gypsum, this property affording a quick test between the two minerals in hand-specimen.

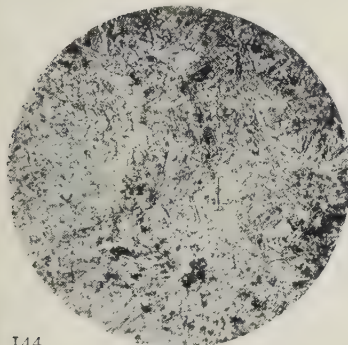
Barite in sediments is frequently in the form of isolated crystalline masses; it seldom achieves the bedded character of the other sulphates, being essentially a vein-mineral, though exceptionally it may result from the weathering of a barite-bearing limestone, thus assuming the character of a residual deposit. Its usual occurrence is in massive, platy, crystalline aggregates, often with prominent and beautifully formed crystals of characteristic habit (p. 137). Earthy and fibrous varieties occur. Colour varies from white to yellow, brown or red according to degree of purity. This mineral is much heavier than the other sulphates here considered, and this constitutes a discriminating test in large specimens; it does not effervesce with acid, which distinguishes it from calcite.



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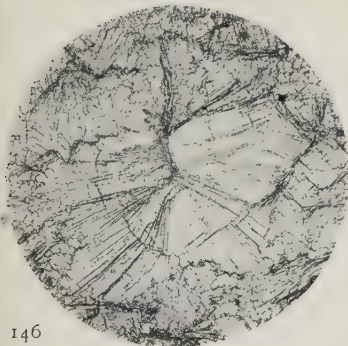
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147

CHLORIDE AND SULPHATE.

- FIG. 142. Rock-Salt (Triassic), Cheshire. [x 15.]
 „ 143. Anhydrite, Cropwell Bishop, Notts. [Bladed Type, x 15.]
 „ 144. do. Cote Hill, Cumberland. [Granular Type, x 23.]
 „ 145. do. Cropwell Bishop, Notts. [Foliated Type, x 15.]
 „ 146. do. Segeberg, Germany. [Spherulitic (radial) type, x 15.]
 „ 147. Anhydrite-Gypsum Rock (Permian), Hatfield, nr. Doncaster, Yorks. [Crossed Nicols, x 25.]

Celestite generally appears in granular masses or as an aggregate of fibrous crystals. Some degree of cleavage is usually apparent. Colour white or cream.

These sulphates seldom occur free of impurity in the rock-form; every gradation is met with between the slightly contaminated mineral substance to those development in which sands, marls, clays, shales, limestones, etc., are intimately associated; various stages of replacement of limestone by the sulphates are possible and are observed.

In some cases it will be found that neither megascopic nor microscopic examination will result in positive identification of each mineral without recourse to physical and chemical tests. The variations of these deposits are so very great, and the possibility of more than one species being closely associated with another in the same sample, renders it always desirable to conduct confirmatory tests. At the same time much more can be done with thin sections under the microscope than is generally realized with these materials.

Text. Gypsum: saccharoidal; smooth; rough; friable; earthy; fibrous. Anhydrite: schistose; fibrous; scaly. Barite: fine; crystalline; granular, sometimes laminated. Celestite: granular; coarse; cavernous; massive.

Min. Comp. Gypsum: impurities commonly iron-ore, silica, calcite, clay. Anhydrite: impurities are gypsum, rock-salt, calcite, iron-ores, etc. Barite: impurities commonly silica, metallic ores, hæmatite, marl, sandstone, etc. Celestite: other sulphates, baryto-celestite, baryto-calcite, limestone, metallic ores, etc.

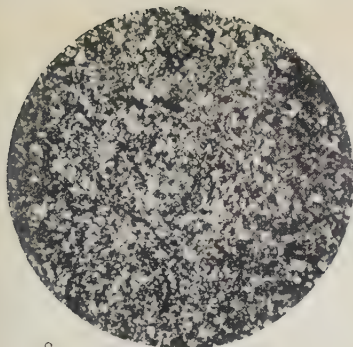
Micro. Gypsum often presents a "porphyritic" structure in thin section under the microscope, when large, prismatic crystals are embedded in a fine crystalline gypsum ground-mass; the large crystals may or may not exhibit tendencies to parallel orientation, usually not. Other modes of occurrence recall the "ophitic" structure of igneous rocks; in this case large platy gypsum crystals enclose well-formed euhedra. Mutually interfering crystalline types present a granulitic structure. Bunches of fine gypsum needles may form in irregular fashion or as spherulites or partial spherulites, the latter displaying a radial structure. If anhydrite is present, it usually stands out clearly by virtue of its higher refractive index (gypsum is lower than Canada

balsam) and strongly developed cleavages. Specks of iron-ore, veins of other minerals, patches of distinctive colouring matter, are all common features of this rock-type.

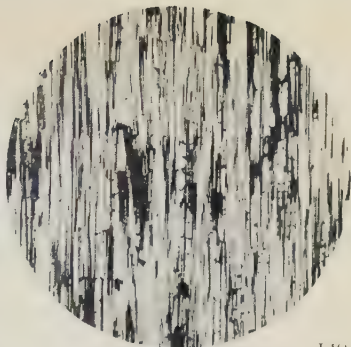
Anhydrite is usually much more coarsely crystallized than gypsum, often in very marked rectangular, prismatic crystals packed together, often orientated in one direction within the boundaries of distinct aggregates. A pseudo-cubic cleavage is normally conspicuous. Other modes of occurrence are spherulitic, radial, irregular clusters, granular (when the rock is made up of scattered stumpy rectangular grains set in an extremely uniform matrix), aggregates of rounded (? corroded) grains, and "feathery" forms. In many examples every stage in the conversion of anhydrite to gypsum may be detected; alternating layers of anhydrite and gypsum are characteristic in some developments, yielding a laminar structure. The passage of limestone into anhydrite may be observed in appropriate examples, especially in dolomitic rocks.

Barite varies considerably from coarsely crystalline types (somewhat rare) to aggregates of mutually interferent crystals of prismatic or granular habit; sometimes the mineral is extremely compact and almost cryptocrystalline. A tendency to develop curved laminæ is not uncommon. Impurities are on the whole commoner than with gypsum and anhydrite, and are frequently identifiable as definite minerals or rock-particles. The earthy type is hard to distinguish from other sulphates by microscopical means alone, as, in fact, are often the crystalline developments; sometimes the alternating glassy and dull white, opaque lustre by reflected light—exhibited by certain forms of the mineral—is sufficiently diagnostic. It has a much higher refractive index than either gypsum or anhydrite. Although possessing similar cleavages to the latter, it seldom displays the markedly "cubic" structures of that mineral.

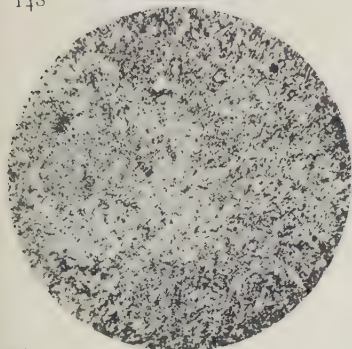
Celestite is so very close in its properties to anhydrite that microscopical distinction is seldom possible; confirmatory tests should always be sought if this mineral is suspected. A bluish tinge to the platy crystals or to the fibrous forms (if developed) is very characteristic; the occurrence of scattered aggregates of fine, fibrous crystals in an otherwise homogeneous



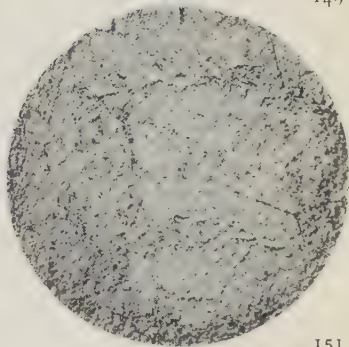
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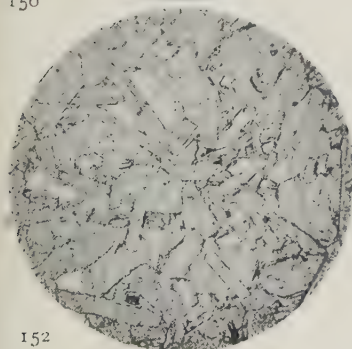
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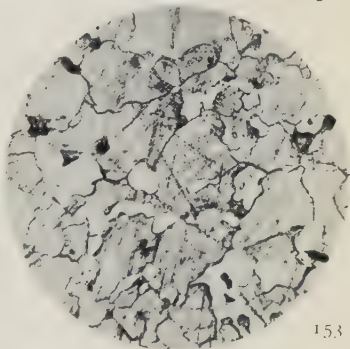
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153

SULPHATE AND NITRATE.

- FIG. 148. Gypsum (Permian), Kirkby Thore, Cumberland.* [x 25.]
 .. 149. "Satin Spar" (Fibrous Gypsum), Nottinghamshire.* [x 25.]
 .. 150. Gypsum (Purbeckian), Sub-Wealden Boring, Sussex.* [x 15.]
 .. 151. Celestite, Yate, Gloucestershire. [x 15.]
 .. 152. Barite, Patterdale, Cumberland. [x 14.]
 .. 153. Nitrate ("Nitratine"), Antofagasta, Chile. [x 20.]

[* Crossed Nicols.]

granular ground-mass, is suggestive of celestite, while in most examples the interference colours are of a lower order than anhydrite or barite.

Types. *Gypsum*: Permian, Kirkby Thore, Westmorland;¹ from the Upper Marls (Permian) of Nottinghamshire and Yorkshire; from the Saliferous Marls (Permian) of Durham; from the Keuper Marls (Trias) of Nottinghamshire,² Derbyshire, Leicestershire, etc.; from the Purbeck (Sub-Wealden Boring), near Battle, Sussex (free of anhydrite).³

Anhydrite: localities as above, except Sussex.⁴

Barite: chiefly as vein-stone from Palæozoic formations in Northumberland, Durham, Westmorland, Shropshire and Welsh Borders; residual material (Carboniferous Limestone) Bradwell Moor, Derbyshire; concretionary crystalline masses in Fullers Earth, Nutfield, Surrey.⁵

Celestite: Trias, Keuper Marl, Yate district, Gloucestershire, in sporadic masses and lenticles.⁶

Ref. ¹ *Mem. Geol. Surv., Spec. Rep. Min. Res., Gt. Brit.*, iii., 1915.

² W. A. Richardson, *Mineralogical Mag.*, xix., 1920, p. 77 & 1921, pp. 196-207.

^{3, 4, 6} *Mem. Geol. Surv., op cit.*

⁵ *Mem. Geol. Surv., Spec. Rep. Min. Res., Gt. Brit.*, ii., 1922.

General Reference.

A. W. Grabau, *Principles of Salt Deposition*, 1920.

(C4. 3) **NITRATES AND BORATES.** [Fig. 153, Pl. xxxv.

Nitrates are exemplified by the sodium nitrate or "caliche" deposits of Chili and Peru, the borates by borax (or the crystallized mineral "tincal") of volcanic origin in Tuscany, etc. From a petrological standpoint, these are comparatively unimportant rocks. The commonest example, soda nitre (Nitratine), is a white, grey or yellow, soft, rather earthy material; it is crystalline, like calcite, and "twinkles" with plane polarised light. There are many varieties of nitrate compounded with calcium, magnesium salts, etc., for which reference must be made to appropriate literature (see below). Borax crystallizes in the monoclinic system and occurs as fine, slender crystals embedded in mud. "Tincal" is the crude mineral.

General References.

- G. W. Tyrrell, *Principles of Petrology*, 1926, p. 232.
F. W. Clarke, *Data of Geochemistry*, U.S.G.S., Bull.
770, 1924, pp. 243-260.
A. W. Grabau, *Principles of Salt Deposition*, 1920.
R. A. F. Penrose, *Journ. Geol.*, xviii., 1910.

CHAPTER VIII.

THE PRINCIPLES AND PRACTICE OF DIFFERENTIATION AND CORRELATION OF SEDIMENTS BY PETROGRAPHIC METHODS.

The Geographical Cycle—Provenance—The Distributive Province—Relation of Sediments to Parent-Rocks — Conditions of Deposition—Technique of Application of Petrographic Methods—Schedule of Information to be obtained from Heavy Mineral Assemblages—Deductions from Records — Special Cases and Difficulties—Thin Section Correlation—The Methods applied to Igneous Rocks.

The basic principles underlying the technique of differentiating or correlating strata by means of their stable mineral components are essentially those fundamental to the science of geology. No new or fantastic theories have had to be invoked to support their validity in this connexion, or their use in this particular application to determinative stratigraphy.

These principles are practically all embodied in the modern conception of the geographical cycle, in its geological interpretation. Briefly stated, the cycle implies terrestrial uplift of a base-levelled or peneplained region; consequent reanimation of the forces of denudation; their slow operation in wearing down this newly formed land-surface; and the persistence of these forces until a new base-level is once more attained. The complete cycle is thus a geological episode and modern stratigraphy owes much to the recognition of these periodic recurrences. Expressed in another way, it is the

alternation of geosynclinal and orogenic phases of earth-history.

Now this kind of cycle of geological events can, for our purpose, be broadly construed as a cycle of sedimentation. The newly uplifted land-mass, composed of igneous or sedimentary rocks, undergoes subærial denudation and from the very first incident of destruction gives rise to a new sediment. With continued disintegration of the mother-rocks there is built up a collateral sedimentary deposit derived therefrom; so the process matures with the achievement of the base-level phase, assuming no interruptions of a diastrophic or similar disturbing character. Thereafter this newly-formed and, by this time, consolidated sediment itself becomes involved in orogenic movements and, probably rent and deformed with igneous intrusions, rises to initiate the next cycle of sedimentation.

Naturally the conditions under which such cycles are achieved vary widely under the influence of climate and the area of the earth's surface affected. We may contrast the normal cycle as outlined above with the arid cycle determined under desert conditions; also the results of upheaval of a comparatively restricted area of a continent with those accruing from a widespread movement which, like the great Alpine movements, encircle nearly half the globe. In this work it is important to keep both such perspectives in view. But whatever the magnitude of the cycle under investigation, whether in space or time, the simple principles which it implies constitute the foundation of our work, and should be constantly kept in mind.

It is necessary to examine the component factors of the sedimentation cycle in further detail. First

of all, the newly uplifted land-mass; this, or the rocks of which it is composed, is essentially the provenance of the sediment formed by its denudation. The term provenance implies source of origin; but, in addition, it has been found convenient in petrographic work to introduce some qualifying definition which enables that source to be visualized as a geological entity. The term "Distributive Province,"¹ first introduced by A. Brammall, has been adopted, and implies the environment embracing all rocks, igneous, metamorphic and sedimentary, contributing to the formation of contemporaneously accumulated sediment. It is essentially the rocks of the distributive province which, on weathering, yield up their minerals, the stable species to survive rigours of chemical reaction and mechanical transport, the unstable components to perish. The more diversified the rocks of the distributive province, the more variable the sediment formed from it. In some cases the province may be entirely sedimentary; this implies that the sediment formed receives its constituents second-hand; in other words, it represents redeposition of a pre-existing sediment. By contrast, disintegration of igneous rocks furnishes primary sediments.

Conversely, the accessory minerals of a sediment, sometimes individually, generally collectively, constitute a measure of its provenance, leading to a reconstruction of the nature of the distributive province, even though all traces of this may long since have disappeared. This is because certain minerals or groups of paragenetic species are inferential of definite rock-types. Thus the reciprocal relationship between provenance and

¹ In H. B. Milner, *Q.J.G.S.*, lxxviii., 1922, p. 366.

sedimentary rock is always kept in view in this work.

The next factor concerns the transference of released mineral matter from parent-rock to basin of sedimentary accumulation, and the circumstances under which such transference takes place. Two important influences exert control; the mechanical agency or medium of transport is one; chemical destabilisation, the tendency of many rock-forming minerals to undergo decomposition when released by denudation, is the other. Mechanical forces, whether wind, water or ice, largely determine the ultimate physical forms of the derived mineral grains; to these forces such inherent properties of minerals as hardness, gravity, cleavage, etc., react in different ways according to their fundamental molecular constitution; shape and size of mineral particles are likewise functions of them. Chemical weathering attacks the less stable rock-forming minerals, which are thus decomposed, formed into secondary products and dispersed in solution, finally to reappear in most cases as authigenic constituents. Every sediment bears the impress of this destabilising environment to a greater or lesser degree; it is essentially its sifting influence which tends to restrict the number of critical heavy minerals which survive, thus enhancing their indicative value.

Neglecting for the moment the time-factor required for this transference of material, it will be clear that successive phases of denudation will promote corresponding phases of sedimentation. If this is reduced to the mathematical conception of plane-surfaces, then we can imagine an infinite series of denudation planes having their counterparts in equivalent sedimentation planes. Thus

the accumulation of a given thickness of sediment will represent the destruction of a corresponding and directly related thickness of parent-rock.

Now if the original parent-rock is homogeneous in composition throughout the cycle of erosion, then it follows that a sediment equally homogeneous in composition will result, *ceteris paribus*. But if the parent-rocks vary in composition with progressive denudation, so the contemporarily formed sediments will indicate, by change of stable accessory minerals, such inherent variations of provenance; the sediments will, in fact, themselves exhibit mineral variation to a corresponding degree which thus becomes characteristic of them. And if there is definite mineral variation in a given thickness of sediment, then recognition of the degree of that variation and of the planes or zones at which it takes place, furnish criteria of subdivision of that sediment. This, then, is the basis of differentiation of sedimentary deposits by means of stable, chiefly heavy mineral, variants.

It further follows that if these heavy minerals have any potential value as indices of differentiation or correlation of the sediments to which they are indigenous, they must, like fossils, have a reasonably restricted range in space and time, especially the latter. This depends again on the rocks of the distributive province; the more varied in mineralogical composition are these, the more definite will be the sedimentary mineral zones.

The comparison between detrital minerals and fossils, however, is a dangerous one, principally for the fact that mineral species, unlike fossil species, do recur after temporary "extinction," similar groups of minerals reappearing time and again throughout the geological record; but, as will be shown, not in such a way as to vitiate their

use in each special circumstance. Notwithstanding this, the simile is a convenient one providing it be not unduly stretched. Actually, mineral "zones" are seldom sharply defined; gradual transition (in a conformable series of strata) is the more general condition proved; this state of things is conveniently illustrated in the diagrams (figs. 154-55).

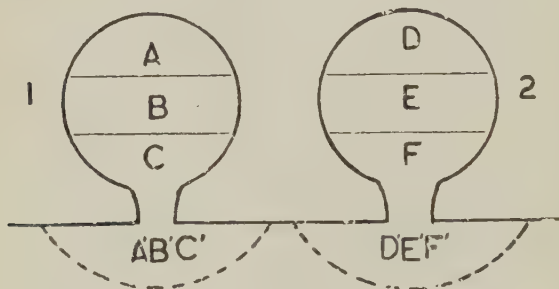


Fig. 154.

A, B, C, D, E and F (fig. 154) represent different rock-types in two distributive provinces (1) and (2) respectively. The initial denudation of (1) and (2) starts, possibly, with C and F respectively; the first types of sediment to be laid down (C' and F') will therefore have decided C and F affinities. As the drainage is cut back, B and E contribute material, the transition being marked by sediment with bC and eF affinities respectively (the smaller letter in each case denoting the lesser influence). With the progressive advance of denudation, both B and E assume importance, with the result that still newer deposits B' and E' are evolved. Similarly A and D contribute the deposits A' and D' respectively. Ultimately vertical sections in the newly-formed deposits will dis-

close successions as indicated in the diagram (fig. 155), bC' , aB' , eF' and dE' being the transitional zones from one horizon to another.

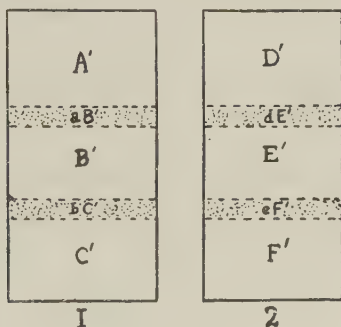


Fig. 155.

Contrasted with such vertical differentiation of sediments is the important and, in many respects, more difficult application of accessory minerals to areal correlation, *i.e.*, the comparison of these indices from place to place, and the assessment of their similarity or dissimilarity as a basis of correlating the sediments to which they pertain. Examples are furnished within limited areas by the comparison of samples from a series of wells on a given oilfield where, perhaps, only a few square miles of a formation is concerned; or over a much wider area, by comparison of samples collected from isolated outcrops or from different points across a long stretch of country. Whatever the area involved, however, the guiding principles are the same as before, with the addition of one uncertain factor: the vagaries of spacial distribution of material. This requires explanation.

In the case of differentiating sediments in vertical succession as described, we are dealing with a restricted column of rock in which the chances are most favourable to the manifestation of every variation, however subtle or striking. With lateral correlation, a vast area has to be explored (comparatively) and variations which may or may not be entirely due to the influence of parent-rocks have to be taken into account.

So long as one fairly definite distributive province has been laid under contribution, the formation may be expected to carry distinctive mineral characters throughout its entire development; comparison of samples from different places will tend to show mechanical rather than mineralogical variation. The reason of this is to be sought in the original distribution of material during the phase of sedimentation concerned. Now, distribution is to a large extent independent of the nature and provenance of detritus; neither, as it affects the present conception, is it solely a question of mechanical agencies of transport. The actual medium in which the material is distributed is of equal importance.

Consider marine conditions. Distribution of sediment, apart from land-drainage, is controlled by the ocean; its currents and their directions; the width and configuration of the continental shelf; depth of water; magnitude of the sedimentary load; size of particle; physiographical factors, climate, etc. Along any one time-plane lithology may change rapidly; the stable mineral supply may become impoverished; the grade-size of the sediment may diminish so considerably that recognition of an anticipated mineral suite may be almost impossible. Yet these are the conditions normally met with.

Again, the conception of two or more distinct distributive provinces contributing their quotas of material to sediment accumulating in a common basin, is very real; present-day examples of this are numerous; similar circumstances have clearly operated constantly in past geological history. Under such conditions there is continual intermingling of different mineral suites; at some stages one suite predominates, at others, another; equally there will be periods when each exerts a similar amount of influence. Or it may be that the drift of sediment, the product of one particular province, may determine intermingling with the product of another province geographically far removed, while beyond the zone of drift, the product of the latter province may occur exclusively. All three sediments co-exist in a common basin, the two distinctive products and their compounded elements in the "overlap" zone. They may clearly be contemporaneous in point of time and will probably be characterized by a common fauna throughout. It is essentially the mineral composition which will vary, and, in such an example as this, to an extent which practically vitiates any correlation over large areas. It is for this reason unsafe to push the application of petrographic methods too far in areal stratigraphy, and to this extent the limitations of the technique must be constantly borne in mind. The principles discussed in this connexion will perhaps be more firmly grasped by means of the accompanying diagram (*fig. 156*).

This shows the prevalent current travelling in a direction from the first to the second province, parallel to the shore-line. While the sedimentary series A'—C' would preserve local individuality, their lateral displacement due to the current would

cause contamination of and interdigitation with the series D'—F', indicated by the shaded area in the figure. Thus in specific cases the composition of the mixed sediments might be represented by c'F', b'E', etc., c' and b' connoting the introduction of material from the first province. Beyond the zone of mixing, sediments D'E'F' preserve their fundamental characters; clearly the mineral composition of A'B'C' may be vastly different from that of D'E'F', yet assuming contemporaneity of

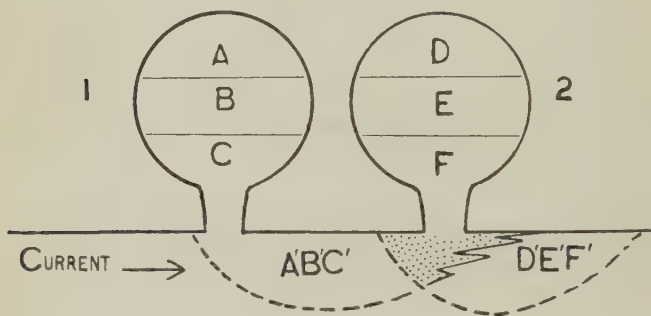


Fig. 156.

deposition, they are theoretically correlative on any other grounds.

From this exposition of first principles, we may now turn to a consideration of the technique involved in their application. At the outset a word of warning is necessary. As in most other branches of specialized science, experience counts for everything. However well the theoretical aspects of the subject may be assimilated, nothing but complete mastery of the method and scope of investigation will lead to success. The first essential is proficiency in diagnosis of minerals as

detrital grains. This will be found a vastly different proposition from familiarity with such minerals as museum specimens or as constituents of rocks studied by means of thin sections.

The cult of the detrital mineral is well worth following; apart from its obvious application to problems in economic geology, its study opens up a wealth of interest, especially when the natural history of a sediment is the motive of the work. But it is necessary to begin at the beginning. Competent diagnosis of detrital minerals, from the ubiquitous quartz to the rarest species, rests only with continual study of examples from as many different sources as possible. Only in this way can the innumerable variations of detrital minerals be learnt and accuracy in application achieved.

The beginner is advised to procure for himself a set of microscope slides of the commoner minerals—concentrates of individual species—and to study these exhaustively. A good list to start on is as follows:—*quartz, microcline, glauconite, calcite, ilmenite, pyrite, leucoxene, tourmaline, staurolite, garnet, rutile, zircon, muscovite, biotite, kyanite, andalusite, topaz*. Two or three mounts of each species from different geological horizons should, if possible, be obtained, and thus certain variations appreciated. The choice should also be made with a view to selecting concentrates of different grade-sizes, so that the minutest particles may receive as much attention as those of larger dimensions. In each instance learn the essential crystallography first. Study the normal crystal habits of the mineral with a good text-book of mineralogy, and then with the aid of the information detailed in Chapter VI of this book, work out the nature and degree of detrital modification.

To the science of crystallography many

students do not hesitate to express a certain apathy; there may be something to be said for this, but the author hastens to assure his reader that it implies an intelligent use of the text-book and an understanding of the elementary principles of the science, especially as regards the optical physics involved; "stereographic projection" and the higher mathematics of the subject are not necessary for this particular work; relieved of that, crystallography can be made a most fascinating study, doubly accentuated when it is correctly applied to the reading of mineral grains under the microscope.

From the study of individual mineral concentrates as suggested, procedure should be in the direction of detrital mineral suites isolated from well-known stratigraphical units. In this connexion a selection might appropriately be made from the Inferior Oolite, Corallian, Lower Greensand, one of the Lower London Tertiaries, *e.g.*, Thanet Sands of the London Basin, the Bagshot Sand, Pliocene sand from East Anglia, and any drift deposit; good examples of the latter occur in most of the plateau deposits of the home counties. Additionally an alluvial sand, a desert sand and a glacial sand should be obtained for the study of contrasted shapes of the particles in each case. With this as foundation, no time need be lost in proceeding to the more uncommon minerals, either studied as individual concentrates or as constituents of specific mineral assemblages. Moreover, throughout the training, learn to exact the fullest powers of the microscope; on its efficient employment depends the difference between crude and really competent work.

The next stage is an attempt at differentiation of two well-known stratigraphical formations.

Comparison of any two slides of the residues from examples above suggested will indicate at once the variations which serve to distinguish them. Those whose facilities do not extend to investigating British formations in this manner, are advised to choose any two well-known deposits in their area, preferably two separated by a considerable geologic time-interval; thereafter this interval should be gradually reduced until the investigations concern horizons in the same formation. It will probably be found that it is this phase of the work which presents the first real difficulties. Even the novice seldom fails to recognize essential differences between mineral suites of two widely separated (in time) deposits; it is the splitting up of a "straight sequence" of beds representing one formation which calls for experienced observation.

From differentiation of beds in vertical succession, attention should be turned to a simple problem of correlation, say, the examination of a series of samples collected from isolated outcrops of a known formation, or from three or four outliers, etc. A further valuable test is to trace the variation through a deposit along the strike over some distance (50 miles), keeping to a constant horizon either lithologically or, better still, palæontologically determined. This should be supplemented by similar work over wide outcrops in directions at right angles to the original shoreline.

Investigation of subsurface rock-samples is but a particular case of the technique of differentiation and correlation by mineral grains, but with this important difference; whereas with surface work the rocks themselves, their lithology, developments and structures in which they are involved, are all exposed to the eye (and to this ex-

tent is their investigation facilitated), rocks studied by means of boring-samples may lie deeply buried under younger deposits or a thick covering of drift, hidden for all time, or possibly outcropping many miles away from the area concerned. This is especially the state of things prone to occur in oilfield geology wherein these petrographic methods find one of their most valued applications. This kind of subsurface research requires the highest degree of skill in handling mineral residues for differentiating a vertical sequence of samples furnished by numerous oil-wells; in comparing them *areally* at known depths (correlation) so as to trace out the attitude of an important stratum; it also calls for intelligent and restrained deduction as a basis of defining subsurface structure.

The latter problem is frequently the most difficult of all. It cannot be too strongly emphasized that incompetent work with heavy minerals leads to disaster more rapidly than any other known weapon of attack in the geological armoury; a careless mistake in identification or an incautious interpretation of microscopical analysis may easily lead to costly error, a matter of no small moment in the economics of petroleum development. But perhaps of more importance is the harm done to the science by such slovenly work. Unfortunately, examples of this are not wanting, and in more than one instance known to the author heavy mineral methods have earned a measure of opprobrium which they little deserved.

In petrographic methods biassed to this particular line of enquiry, the personal equation looms large. No two operators work on precisely the same plan, and what may appear to be subtle though convincing proof of distinction to one, may

be passed over in favour of alternative evidence by the other. This, from the very nature of the investigations, is bound to be the case. In most branches of analytical geology there are more ways than one of arriving at the accepted conclusion. After all, the main thing is to achieve accuracy; the actual method of attaining it matters little so long as it is scientific and is fully justified by the principles laid down. The reader has only to compare different published accounts of heavy mineral analysis and correlation to perceive the truth of these remarks.

Accordingly, in such circumstances no hard and fast rules can be laid down in the actual process of differentiation and correlation by these methods, nor would the best interests of the work be served by any attempt to standardize technique. On the other hand, experience has taught a certain routine which has been found satisfactory and adequate to every problem worked out by the author. It has the merit of being straightforward; it does not imply an inordinate amount of time to achieve results; it does not attempt the impracticable task of reducing mineral assemblages to mathematical formulæ; and it may be claimed to be sufficiently elastic to meet every contingency in which the methods may be invoked. The reader will not go far wrong if he follows along similar lines; doubtless, when he has acquired his experience, he will be able to make many improvements in detail.

Starting with the microscope slides of the minerals under investigation, two courses are open, according to the nature of the work. If it is to be exhaustive, and time is not an important item, three slides per sample should be made. One of these is the original sediment, either in its

natural state, if incoherent, or gently pulverized, if consolidated. Another is a mount of the cleaned, light sediment (*i.e.*, S.G.<2.9, p. 44). The third is the total heavy residue. The object of this triplication is to safeguard against loss of any soft or soluble mineral during the process of cleaning the sample, etc. Also, many instances occur where these light minerals are as important, if not actually more so, than the heavy constituents.

Where, however, previous knowledge of the sediment discounts the chance of the light minerals serving useful purpose, or where, as in much economic work, time is a vital factor, then the light and original mounts may be dispensed with, and investigations proceed entirely on the basis of the heavy mineral residue. The operator must use his own discretion in the matter.

Triplication of slides necessarily implies much additional labour in preparation, but actual microscopical examination of the light crop and original sample takes only a fraction of the time occupied with the heavy residue. In the author's view, if the light minerals are neglected altogether, there is always the feeling that some important feature has been passed over, that the sudden influx of minute organisms, or minerals like feldspar or glauconite, has been missed, when any one of these components might have proved valuable.

The practice of isolating magnetic and non-magnetic crops of minerals and employing separate mounts for each, while essential in academic research, may be found impracticable in economic work; the total heavy residue, or a proportionate part of it, is then the basis of comparison. It is often difficult to carry in one's mind the salient features of several assemblages when attempting their differentia-

tion, especially if the number of samples is large, a difficulty much enhanced by duplicating every slide. This has reference entirely to economic work; as stated above, where time is no object and where the most detailed investigations are contemplated, circumstances are altered, and even six slides of one sample, two high gravity concentrates in addition to original, light, magnetic and non-magnetic crops, may be essential. The author has had occasion to use a dozen mineral segregations (each involving special preparation, and an equal number of mounts) from one concentrate in order to reach exhaustive quantitative and qualitative results from certain special samples.

The slides of the respective mineral residues to be examined are first sorted out in some definite order, according to depth (oil-well samples), geographical or other position (field-samples), or in numerical order if there is nothing else to determine the arrangement. Next, every slide in succession is rapidly examined under the microscope, any striking similarities or dissimilarities being segregated at the outset into groups. [N.B.—It is convenient to use a series of cardboard specimen-trays, about 4" x 5", to accommodate each group of slides.] The groups form the basis of subsequent methodical examination, leading to confirmation of the initial segregation, and to further subdivision of the slides, hence of the samples they represent. The object of this preliminary "run through" is to enable one to grasp at the outset the main features of the mineral suites; much may be discernible in the process; it is seldom that it is not so. But at least a valuable first impression of the problem ahead is gained, and for this reason, if for no other, this preliminary survey is desirable.

To work diligently through, say, two hundred well-sample residues (by no means an uncommon job in an oilfield laboratory!) without any idea what the two hundredth is like until, after long effort, it is ultimately reached, can prove a most disconcerting performance.

The following schedule of information is next sought :—

- (1) Identification of minerals.
- (2) Notification of minerals with special crystallographical features (other than accidental occurrences).
- (3) Notification of minerals with special physical features (other than rare occurrences).
- (4) Notification of minerals with special optical properties.
- (5) Relative frequency of occurrence of individual minerals.
- (6) Reciprocal relationship between two or more prominent minerals.
- (7) Grade-size or sizes of predominant minerals present.
- (8) Average shape of prominent (common) minerals present.
- (9) Any particularly striking feature (or mineral) sufficiently prominent to constitute an index of the sample concerned.
- (10) Character of total assemblage.

The schedule in itself looks somewhat formidable, but in actual practice the experienced operator checks up this information almost subconsciously and enters it on his record, at the same time carrying in his memory the salient features, of whatever nature, of any unique or striking assemblages examined. A facsimile of the form devised by the author for recording this information is illustrated in *fig. 157*, pp. 376-7.

For the benefit of the novice, the ten items in the above schedule are here annotated:—

(1) *Identification*. In view of what has already been written on this point, little remains to be added. Diagnosis can never be too thorough and the greatest accuracy is absolutely essential. In some cases, one hundred per cent. identification may be impossible, especially with very fine grade sediments; in other cases a problem mineral may present itself which defies positive diagnosis in the time or with the facilities at hand. If such a mineral is adventitious, just occurring in one or two samples only, it may probably be neglected with safety; if it ranges through a number of associated samples in such a manner as to constitute a feature of those samples, then it is necessary to recognize it by some make-shift designation, *e.g.*, "Mineral X." Ultimately, of course, the enthusiastic worker will not be content until he has found a mineralogical "value" for "X" (p. 104). A further point to note is that a mere list of mineral occurrences is *per se* seldom of much value; it is the rest of the qualifying information, covered by the schedule, which determines its utility, a remark applying equally to mineral residues segregated from crushed igneous rocks (p. 407). For further aid in diagnosis, see pp. 427-28.

There is no particular order in which minerals should be determined or recorded, though there is some convenience in listing light species first, followed by the iron-ores, then by the common non-opaque minerals, working down to the scarce occurrences at the bottom of the list. In published records, however, the arrangement of the minerals by crystal systems has much in its favour.¹

(2) *Special Crystallographical Features* include well preserved crystals of a mineral (euhedra); striking development of subsidiary faces (*e.g.*, the "facetted" of zircon); prominent terminations (*e.g.*, acute bipyramids); twins (*e.g.*, geniculate twins of rutile); also striations, zoning, inclusions and any obvious inherent structures. Any prominent varietal features of a given mineral traced through a series of samples may quite likely result in turning the scale in favour of their correlation. In other directions, varietal features of minerals have decided bearing on questions of provenance.² Inclusions, especially in quartz, are

¹ H. H. Thomas, *Q.J.G.S.*, lxx., 1909, p. 231.

² P. G. H. Boswell, *Mineralogical Mag.*, xxi., 1927, pp. 310-317; also A. Brammall, *Proc. Geol. Assoc.*, xxxix., 1928, pp. 27-48.

of value in determining parent-rocks.¹ Even absence of crystallization may, in some cases, prove a valuable characteristic of some prominent species.

(3) *Physical Features* amenable to microscopic determination concern chiefly colour, lustre, and grain "morphology." Colour, or its absence, is an important criterion of identification. Colouring matter may be uniform or partial; for instance, some sapphire grains are uniformly blue, others from different sources have their colour dispersed in patches, giving a blotchy appearance. Parti-colouring (e.g., brown-green tourmaline) may prove a distinctive feature. Vivid colours are noteworthy since most detrital minerals exhibit somewhat subdued colouring. A definite coloured mineral, e.g., purple zircon, may prove a critical indicator of a deposit, equally of its provenance.² A common mineral occurring in an uncommon colour would constitute a valuable index of the samples in which it was found, e.g., naturally pink andalusite, green garnet. Lustre, determined by good artificial incident light, needs no stress here.

Grain "morphology" is a convenient expression to describe the external form of mineral-fragments. It is not merely a record of shape and size, though these properties could appropriately be classed in this category (see (7) and (8) below), but rather the structure of the grain, the contrast between acicular and granular developments, between fibrous and crystalline, etc. Examples in which grain morphology has proved critical in differentiation are the temporary appearance of actinolite (fibrous hornblende) at one horizon of an amphibole-rich deposit; granular titanite as characteristic of a zone in a deposit otherwise marked by ragged, irregular grains of the same species; and the co-existence of spheroidal and irregular grains of siderite.

(4) *Optical Properties* of minerals, especially where they are of an unusual character or of pronounced development, are among the most important criteria of distinction. Pleochroism and the nature of the interference figure (if any) are the two most sought after features. Normally pleochroic minerals vary considerably in intensity of pleochroism: this constitutes the criterion, and many examples could be given. Among the best from the author's notebooks are the intense blood-red pleochroism of andalusite from the Cornish Pliocene; the vivid brown-green pleo-

¹ A. Gilligan, *Q.J.G.S.*, lxxv., 1919, pp. 260-262.

² P. G. H. Boswell, *op. cit.*

chroism of hypersthene from a Quarternary sand of Martinique; the deep mauve pleochroism of glaucophane from certain Miocene silts of Trinidad and Venezuela; the olive-green to slaty blue pleochroism of chloritoid from the Bridport Sands of Dorset. In each case the striking colour-change distinguishes the mineral, which in turn distinguishes the samples in which it is found. The examples could be multiplied many times; some of the best minerals in which to anticipate unique or distinctive pleochroism, apart from those mentioned above, are the amphiboles, tourmaline and staurolite.

In the matter of interference figures, the maximum information obtainable from these depends on ability in their interpretation. The mere observation of uniaxial or biaxial character is seldom of more than slight diagnostic value; an exception is the occasional occurrence of undoubted biaxial zircon; this would certainly prove indicative of the samples in which it was found. The kind of optical research implied is well illustrated by Brammell's work on the Dartmoor brookite,¹ and as demonstrated by that author, it connotes nothing less than careful optical measurements, observations of the behaviour of the figure, in particular its colour-bands, on rotation, etc. Those who possess some knowledge of optical physics know how to appreciate and to use this valuable weapon, not only for diagnosis, but for running down a mineral which, apparently normal and of no index-value, becomes critical on account of some determined optical peculiarity; lack of such knowledge renders the observation both empirical and mechanical, and constitutes a serious disadvantage in this kind of research. Other examples of critical interference figures of detrital minerals from the author's experience are the comparatively large axial angle of some black mica ($\pm 30^\circ$) suggesting phlogopite (diagnosis not apparent from the mineral itself); very large axial angle in some muscovite flakes; some basal quartz grains which showed abnormal "splitting" of the cross on rotation; the eccentric, partial interference figure of a deeply coloured epidote; the optical characters of brookite, axinite and titanite; certain varieties of topaz with smaller axial angle than usual and very prominent crimson colour-bands.

(5) *Frequency.* If there is a mild "bone of contention" among petrographers, it concerns methods of estimating, still more of reporting relative proportional occurrences

¹ *op. cit.*

of minerals in a given assemblage. All are agreed that frequency statements, if accurate, may have considerable stratigraphical value. In work on differentiation and correlation of sediments, this value is unquestionable. The problem is, how to arrive at an accurate expression without depending too much on purely visual assessment or without going to the other extreme of counting grain by grain, truly a heart-breaking process. Unfortunately, it must be admitted that, at present, the problem is very far from a generally acceptable solution.

Most frequency estimations are undoubtedly by eye, and after continual practice it is, in the author's opinion, possible to arrive at reasonable results, providing the grade-size of the suite is not too small. The finer the grade, the greater the inaccuracy of assessment, assuming a good quantity of residue. Scanty residues in any case lend themselves more readily to accurate estimation, and even counting is then not too onerous. But no two estimations by different persons ever agree. The author has frequently tried this out with his classes of students, and it is surprising what variations exist in apportioning powers. What is abundant to one, is merely common to another; the tendency to attribute predominance to opaque minerals, because they show up sharply against a white background, is another source of error. The conclusion is forced that, except in the circumstances of limited residues of large grade-size, estimation by eye is really inaccurate, therefore of little value.

At the other extreme we have the work of W. F. Fleet,¹ who, in the course of his researches into heavy minerals in rocks of the English Midlands, found that nothing short of counting the grains of a residue gave satisfactory results. He writes, ". . . to obtain accurate results that may readily be compared with those of other workers actual counting of the grains is considered essential . . . at first sight, a tedious task, but it has been found that, using, say, a $\frac{1}{16}$ in. objective with an eye-piece giving a large field, and by employing a mechanical stage, it is not a difficult matter to traverse the whole width of a slide several times, counting every grain. According to the closeness with which the minerals appear on the mount it may be necessary to count the grains in anything from twelve to fifty fields, and the number of grains may range from 500 to 1,000 or even more."

¹ W. F. Fleet, *Geol. Mag.*, lxiii., 1926, pp. 505 *et seq.*

Many American petrographers also have recourse to counting, and their work certainly confirms the findings of W. F. Fleet.

The superiority of this method is unquestioned. Where reliable quantitative results of proportional occurrence of each species are demanded, nothing short of counting is likely to give satisfaction. In our special work, this is definitely the case where the fundamental mineral assemblages from different horizons of a formation are not rich in species or varied; where, in fact, the same minerals tend to occur throughout, and differentiation perforce rests on less obvious variations and on relative frequency of occurrence. In cases where the mineral differences prevailing in two deposits are sufficiently striking, the frequency factor may assume less consequence and qualitative estimation by eye suffice. But since much work carried out decidedly necessitates some numerical expression of frequency, then it would seem that counting is inevitable.

Notwithstanding this, the author has to admit that he remains somewhat heretical on the matter, and for a good reason. Counting of grains is only possible where (a) the number of residues is limited, (b) time is not an important factor, and (c) results are not expected on the "mass-production" principle. Consider for a moment an example in one of many oilfield laboratories known to the author. Here, when at high drilling pressure, as many as 50 to 100 samples may accumulate from a few wells in one day; the field being a youthful one, structural interpretation is awaited impatiently, and critical evidence is desired from each of these samples in the shortest possible time. Supposing the 100 samples to average 1,000 mineral grains each, this means counting no less than 100,000 grains. Translate this into daily routine, as distinct from research with purely scientific motives, and the task becomes almost superhuman; certainly few pairs of eyes could stand the strain long without material damage. The method has actually been tried under the exigencies of oilfield development in more than one instance known to the author, but it had definitely to be abandoned from the sheer impossibility of the individuals to cope with the mental fatigue involved.

As in most things, a compromise is possible. In those circumstances where time and other conditions permit, and where accuracy is urgent, counting should be adopted. In other instances, limit the count to, say, four to six chosen (and representative) fields, and average the results. Where

one person is continually responsible for the results and for any interpretation which may be placed upon them, and where he feels himself sufficiently safe to adhere to the older and quicker method of eye-estimation, let him not be afraid to continue in so doing. He may draw some comfort from the fact that in economic work, where these methods are in vogue in many different centres all over the world, for every grain counted there are probably at least one hundred deemed only worthy of passing inspection.

In the matter of recording frequencies, almost every author seems to have devised his own method, and there is practically no recognized convention. Broadly speaking, the various records fall into one of three categories: descriptive, graphical, and quantitative.

The descriptive method recognizes the use of such terms as "abundant," "common," "scarce," "rare," or "ultra-dominant," "dominant," "frequent," and so on; qualifying adjectives, *e.g.* "very," "exceedingly," etc., are from time to time added to raise or lessen the status of a mineral by a slight amount in the frequency scale. The trouble with such terms is that different authors interpret them in different ways; while everyone may read an unequivocal meaning into two antipathetic expressions such as "rare" and "abundant," it is certainly not so easy to decipher the intended significance, or the actual fact underlying "scarce," "very scarce," "rare," "exceedingly rare" applied to a mineral in a range of samples.

In the original volume of this book, the author suggested the use of some of these terms as in the accompanying table. At the suggestion of Prof. W. W. Watts, each word or symbol was given a number, ranging from 9 downwards, as the mental picture conveyed by comparison of figures rather than of letters of the alphabet is a decided advantage for correlation purposes.

<i>Term.</i>	<i>Symbol.</i>	<i>Proposed Number.</i>
"Flood"	F	9
Very Abundant	A	8
Abundant	a	7
Very Common	C	6
Common	c	5
Scarce	s	4
Very Scarce	S	3
Rare	r	2
Very Rare	R	1

This scheme also embodied the use of the term "flood," implying the occurrence of a particular species far in excess of all others as to constitute almost a pure concentrate. Prof. Boswell¹ has pointed out in one of his papers that "The indication of relative abundance by means of numbers seems first to have been introduced by E. Artini,² whose scale ran from 1=very abundant to 10=very rare. Later F. Salmojrighi³ reversed the order and used the following scheme: 1=exceedingly rare; 2=rare; 3=very scarce; 4=scarce; 5=frequent; 6=very frequent; 7=abundant; 8=very abundant; 9=dominant; 10=ultradominant." Prof. Boswell himself follows this latter scheme.

Another method in vogue with some authors is the use of capital letters, small Roman letters and italics to denote extreme abundance, abundance and scarcity, respectively. Applied to complete mineral composition in the "light" and heavy groups, G. M. Davies remarks,⁴ "Owing to the small percentage of heavy minerals, however, one of them may be marked as 'abundant,' though actually scarcer than a 'scarce' mineral of the lighter group." Thus this simple method also has its drawbacks.

In the graphical method, which has not found general favour, relative frequency is represented by horizontal bars, one bar denoting rare, two bars common, three bars abundant (*fig. 158*). The result works out as in the accompanying table. It represents but little, if any, advance on the descriptive method.⁵

	A	B	C	D	E	F	G	H
Garnet	≡≡≡	≡≡≡	≡≡≡	≡≡≡	—	≡≡≡	≡≡≡	≡≡≡
Spinel	—			—	—			
Magnetite	≡≡≡	≡≡≡	≡≡≡	≡≡≡	≡≡≡	≡≡≡	≡≡≡	≡≡≡

FIG. 158. The letters denote localities.

The quantitative method is simply the expression of frequency results as actual percentages, and implies com-

¹ P. G. H. Boswell, *Q.J.G.S.*, lxxix., 1923, p. 226.

² E. Artini, *Riv. di Min. and Crist. ital.*, xix. (1898), pp. 33-94.

³ F. Salmojrighi, *Rendic. Ist. Lomb. Sci. Lett.*, xl., 1907, pp. 870-87.

⁴ G. M. Davies, *Proc. Croydon Nat. Hist. Soc.*, 1915-16, p. 81.

⁵ E. Neaverson, *Proc. Geol. Assoc.*, xxxvi., 1925, p. 252.

prehensive counting of the grains. It is clearly the only logical method if counting is carried out. In America it has already reached the stage of convention; in this country we owe its exposition principally to W. F. Fleet.¹

Thus from all these methods of determining and recording frequency, the reader has a wide choice, depending on the class of work in hand and on the degree of accuracy aimed at. The author's method is to count and express as percentages where special problems and time allow, and to use the "9 to 1" convention in other circumstances, *i.e.*, in routine work, without worrying very much what each numeral stands for so long as it is understood that "9" implies quantity, "1" rarity, at each end of the scale. Or, in some cases, the record of a mineral may be marked with an asterisk (*) and where, on account of abundance or for some other noteworthy reason, it is deemed necessary to stress it, the asterisk is underlined thus: *. This is a useful method when time is strictly limited, or where more definite expressions of frequency would avail but little in the work.

(6) *Reciprocal Relationship* between two or more prominent species is not an invariable nor an infallible test of distinction, though some interesting examples can sometimes be worked out. For instance, the relative abundance of red and yellow rutile is quite a constant factor for certain beds in the Northumberland Millstone Grit; other examples are the brown-blue tourmaline ratio; (a), (b) and (c) types of zircon (where (a), (b) and (c) represent distinct developments); the ilmenite-leucoxene ratio; Prof. Boswell mentions "a reciprocal relation in the matter of relative abundance appears to exist between sphene on the one hand and anatase and brookite on the other" in connexion with the Upper Lias sands of the west of England.²

Clearly such a reciprocal factor depends for its definition on actual counting; where there appears some chance of establishing it for a given set of beds, or even for a definite horizon, the attempt should be made, since this factor will tend to be an index of that sediment and will consequently have differentiating value. It will be noted that this information constitutes a special case of frequency determination and therefore requires the same cautious procedure as necessary in that connexion.

¹ W. F. Fleet, *op. cit.*; also *Proc. Geol. Assoc.*, xxxviii., 1927, p. 4.

² *Geol. Mag.*, lxi., 1924, p. 257.

(7) *Grade-Size* of predominant minerals is a matter of very great importance, and frequently is of much consequence in the grouping of samples. Methods of arriving at this factor are summarized on pages 108-11. Both average grade-size of total mineral assemblage and grade-size of one or more predominant species may be used as indices of samples in which this factor seems likely to afford a basis of identification; though it must be remembered that change of grade, even abrupt, is not in itself evidence of change of horizon or of formation. Rapid and local lateral variation of facies will thus tend to confuse the issue.

It is relevant to mention here that comparison of total sand-grade (p. 109) through a suite of samples may be useful in their grouping.

In the matter of size of individual grains, this is often a valuable index, especially where one mineral overshadows all others in this respect. Mica is especially liable to occur in grains from twice to four times the dimensions of its associated species. A series of topaz grains, of uniform dimensions between 0.2 mm. and 0.3 mm. in an assemblage of much finer grade, furnishes another example. Garnet, kyanite, sillimanite, and occasionally hornblende, may each occur in similar circumstances, as other species.

For percentage of mineral per grade-size, see p. 108.

(8) *Shape* of minerals enters into comparative diagnosis of samples to a great extent in many problems of correlation. Some residues, *e.g.*, from æolian deposits, are so conspicuously "rounded" as to render this factor alone decisive in grouping the samples of which this is a characteristic feature, when residues of contrasted "angularity" are among those investigated. An unconformity involving æolian beds resting upon aqueous deposits, or *vice versa*, is an example of this. Where "subangularity" is the observed feature, shape will probably be of little determinative importance. On the other hand, marked "angularity" of grain, in appropriate and contrasted shape-association, is of index-value; for instance, ice-borne deposits frequently exhibit this to a marked degree, and may thus be individualized.

Shape of mineral grains is always taken into account in correlation, whether it prove of direct or indirect value; some workers even go so far as to estimate percentages of "rounded," "subangular" and "angular" grains of one common species, *e.g.*, zircon, if this happens to occur

in requisite variety of shape, but in the author's opinion this is seldom likely to supply data commensurate in value with the effort put forward in their acquisition.

(9) *Prominent Features* of detrital minerals, such as constitute *per se* indices of the samples in which they are recognized, often occur and prove invaluable in petrographic methods of correlation. In this category we place not only particularly striking minerals, but also any special feature of one or more species which is sufficiently notable to be utilized as an index. Examples of this include sponge spicules, shell-fragments, nodular pyrite, dolomite rhombs, large mica flakes with included iron-ores, prevalence of (010) kyanite flakes (with straight extinction); magnetite octahedra (fig. 54); knee-shaped twins of rutile; *foraminifera* chambers filled with pyrite, and so on. Anything, in fact, which is characteristic and persistent, also somewhat uncommon, is of value in a residue and should be utilized accordingly.

(10) *Character of Total Assemblage*. In the hands of the experienced operator, a glance at the heavy mineral assemblage isolated from any particular sample, is sufficient to impress its essential characters almost subconsciously; many of the foregoing details are automatically assimilated in shaping assessment of the whole, and in the course of examination of a series of assemblages, certain striking accordances and discordances are noted mainly on cumulative evidence; thus correlation and differentiation proceed guided to no small extent by successive impressions of assemblages.

This grasp of essentials, to which reference has before been made, is really the basis of both rapid and accurate work; it is unquestionably the reward of experience and careful observation; this "assemblage sense" should be cultivated by all serious students of the subject.

To illustrate, many workers on British sediments are familiar with, and can recognize at a glance, the source of origin of a particular heavy mineral suite; this is not an extravagant claim. Such uniform assemblages of minerals obtained from the Inferior Oolite, Lower Greensand, Thanet Sands (Eocene) and Pliocene deposits, are self-evident to those who have investigated these and many other sedimentary rocks from different geological horizons.

It is not easy to put into mere words the significance of the character of an assemblage or the criteria by which that significance may be appreciated and made use of;

instinct plays a large part in the technique. But those who take the trouble to master the above data, may be sure that their grip on this aspect of the subject will be firm and lasting, and that this new knowledge of sedimentary deposits will reveal many unsuspected features tending to individualize particular formations.

From the schedule of information above described, is deduced certain evidence vital to correlation problems, also to the wider questions of natural history of sediments and kindred palæo-geographical data (Ch. X). For present purposes, the desiderata are as follows:—

- (1) Lateral and vertical persistence of minerals.
- (2) Definition of zones in vertical sequence.
- (3) Areal correlation and differentiation.

(1) The lateral persistence of individual minerals connotes their uniform or sporadic distribution, and is an important factor, especially in problems of areal correlation. Such persistence may be expressed in terms of distance from one locality to another, or in the case of a small area where quarries, pits or well-borings yield the evidence, for example, from point to point as dictated by circumstances. It is desirable to construct a persistence diagram for reference in this connexion, and further to estimate the percentage of species which are actually persistent throughout; if this percentage is high (say over 60%) such an estimate may be of great significance. *Fig. 159* shows the type of persistence diagram usually employed. In the diagram a suite of minerals is shown in the left-hand column, and the letters P, Q, R, S and T may be interpreted as different localities, oil-well horizons etc. Other published examples of lateral persistence diagrams are to be found in the references below.¹

¹ H. B. Milner, *Q.J.G.S.*, lxxviii., 1922, p. 365; C. Raeburn & H. B. Milner, *Alluvial Prospecting*, 1927, pp. 79, 81; H. H. Thomas, *Q.J.G.S.*, lxx., 1909, p. 240.

Fig. 159. PERSISTENCE DIAGRAM.

Localities	P	Q	R	S	T
<i>Minerals.</i>					
Magnetite.					
Ilmenite.					
Garnet.					
Tourmaline.					
Staurolite.					
Epidote.					
Biotite.					
Leucoxene.					
Zircon.					
Kyanite.					
Anatase.					
Rutile.					
Topaz.					
Andalusite.					
Spinel.					
Sillimanite					
Titanite.					

The vertical range of a mineral or series of minerals tends to demarcate a zone or group of beds in a formation and a vertical range diagram is sometimes useful in recording such distribution. An example of this type of persistence diagram is given by A. Heard and R. Davies in their paper on the minerals of the Old Red Sandstone.¹

(2) It follows from what has been written that any peculiar properties of minerals isolated from a sedimentary deposit not only individualize the minerals themselves, but extend to that deposit a definite factor of identification. The narrower the limits within which such peculiarities are confined, the greater the possibility of demarcating zones characterized by particular mineral associations or features. As previously explained, differentiation of strata in vertical sequence depends on the narrowing down of these limits, on the separation of one group of beds from another by means of indicative mineral species or assemblages. This naturally follows from a close examination of any series of samples taken from selected intervals in a given sedimentary sequence, along the lines already laid down.

(3) This phase of the work has been explained. It depends on careful comparison of samples taken from different points over a given area. The main possibility of error here is in minimising or neglecting the lateral variation natural to the deposit, an error tending to increase with the distance over which the work is prosecuted.

Such lateral variation usually implies lithology, *i.e.*, grade-size of rock-particles, but it may also imply slight changes in mineral composition. In comparing a series of samples taken from a formation over a given area, one may confidently anticipate a "fundamental mineral suite" which will identify the deposit as a whole and which will serve to establish relationship between them. The great thing to guard against is stretching comparisons too far; it would be foolish to attempt to "correlate" rocks of presumed similar age occurring in two widely separated regions such as Britain and the South of France, for instance, at least by petrographic methods. Any such attempt or its equivalent would naturally prove futile. On the other hand, the author has often been asked to define the limits of areal correlation; this is again impossible, since it must vary in every area in which the work is undertaken. Only a knowledge of the fundamental geology

¹ *Q.J.G.S.*, lxxx., 1924, p. 508.

of the particular country in view can act as a guide; but a safe rule is to err on the side of restriction, or if circumstances suggest that investigations over large areas or great distances are warranted, feel out from one locality to the next with the greatest caution, being constantly on the *qui vive* for abnormalities brought about by the overlapping of two distinctly contributed sediments, or by other complex and fundamental conditions of deposition. The student will soon learn what is practicable and what is not, and no point would be gained here by any attempt to set a boundary to the work behind which procedure may be straightforward, beyond which it is fraught with difficulties and pitfalls.

SPECIAL CASES IN THE APPLICATION OF PETROGRAPHIC METHODS TO CORRELATION AND DIFFERENTIATION PROBLEMS.

There are certain cases where the natural conditions of a sedimentary deposit render it necessary to take special precautions against mistaken interpretation, or where inherent difficulties are raised in the course of investigations. The most important of these will now be dealt with.

Unconformities. Prof. Boswell has remarked that "unconformities are usually emphasized by the changes in mineral composition, and these support palæontological and field evidence."¹ Generally speaking this is true; but frequently local erosion has been such, that what is theoretically conceived as the plane of unconformity, is in reality a zone of unconformity, *i.e.*, an indefinite thickness of sediment, the combined product of contemporaneous erosion and deposition, with a mineralogical composition having affinities with both the older and the younger deposits.

If a series of samples is taken laterally from the points 1, 2, 3, 4 (*fig. 160*), the material collected

¹ *Geol. Mag.*, 1916, p. 164.

will be from a "mixed" zone (dotted), and the mineralogical composition may be represented as follows :—

Sample 1.....ap.	} The small letters are indicative of transitional variations in composition from A to P, B to P, etc.
Sample 2.....bp.	
Sample 3.....cp.	
Sample 4.....dp.	

Accordingly, lateral variation at approximately the same horizon becomes pronounced in these circumstances, and where such a structure is hidden (as it may well be in petroliferous territory which is being explored by the drill), a false impression can easily be drawn from discordances between the "heavy" residues, structural interpretation suffering in consequence.

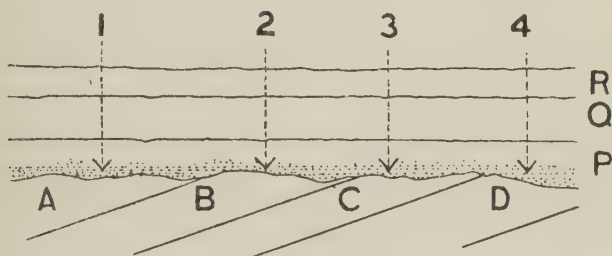


Fig. 160.

The mitigating factor in this case is the tendency for "flooding" of a particular species to occur wherever different beds are subjacent to P, and consequently the four samples may each present this feature and thus furnish a clue to the true state of affairs. The reason for such a tendency to "flooding" is that the actual process of differential erosion of the tilted edges of A, B, C and D tends to eliminate the less stable and gradually concentrate the more stable minerals in any undulations created; the material then becomes mixed

with newly deposited sediment, and in this way not only is the "mixed" zone initiated, but the proportion of "heavy" minerals greatly increased, with probable concomitant "flooding" of one or more species. It is a noteworthy fact that such "flooding," especially of minerals like zircon, epidote, mica, tourmaline, garnet, rutile, etc., is often characteristic of sediments involved within the zone of unconformity.

Current-Bedding. This feature, if developed on a large scale, may prove one of considerable difficulty in using heavy minerals for tracing out horizons. Flooding of the heavier species, much mixing of grades, even of distinctive mineral residues, or the influence of "gravity sorting" may prevail. If the investigations concern outcropping rocks, some attempt at the resolution of the current-bedding into its components should precede any work on the sediment itself. But where a current-bedded deposit is being drilled, and the only evidence available is from well-samples, then the problem becomes an exceedingly complex one, in certain cases impracticable of solution by petrographic methods alone.

Generally, however, it is possible to establish the fundamental mineral suite characteristic of the deposit, irrespective of the amount of disturbance it may reveal, and to this extent one current-bedded formation may be differentiated from a subjacent or superincumbent deposit of different age, or from one unaffected by such false bedding. But any attempt to delimit mineral zones within such a formation is likely to be frustrated very soon; none but the broadest distinctions can be drawn in these circumstances.

In the study of current-bedded rocks over wider areas, the difficulty increases with the

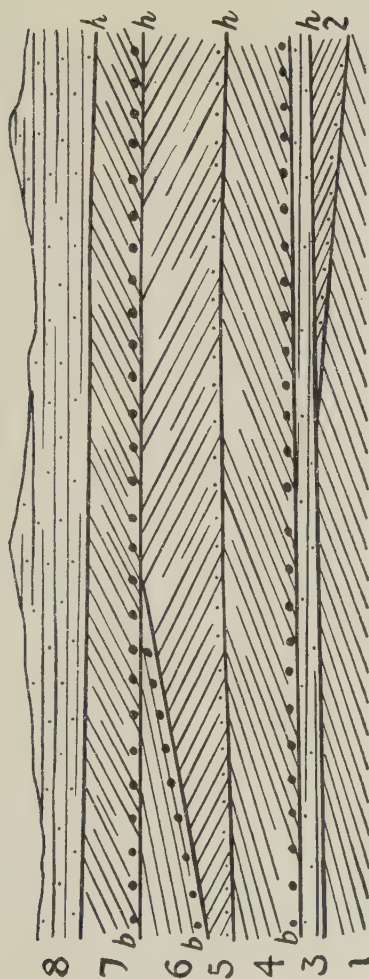


FIG. 161. Heavy Minerals and Current-Bedding.

General horizontal stratification represented by planes *h*; bottomset planes containing greatest quantity of heavy mineral, *b*. Beds 1, 4, 6, 7, indicate directions of prevalent current-trend; beds 2, 5, show discordant direction, with less heavy mineral; beds 3, 8, indicate approximately horizontal stratification (undisturbed deposition), with evenly distributed heavy mineral.

vagaries of the deposits themselves; lateral variation both of minerals and of grades is characteristic and difficult to follow through, unless the exposures are really good and continuous. Under subsurface conditions, detailed work is practically impossible.

The author's investigations of heavy minerals in current-bedded formations reveal the following tendencies which may be helpful in guiding the reader in similar cases:—

(a) In any set of inclined beds, *i.e.*, to the general horizontal stratification, the finest material (grade) occurs at the downward end (bottomset planes) and contains the greatest quantity of heavy mineral (*fig.* 161).

(b) The greater the angle of inclination (never more than 41° according to Thoulet), the greater the quantity of heavy mineral at the downward end; flooding of iron-ores characteristic.

(c) In coarse sands the heavy minerals tend to be more evenly distributed throughout the inclined beds, though segregation of the heaviest constituents at the bottomset end is likely to occur.

(d) The largest yield of heavy mineral from current-bedded sands is obtained from steeply inclined beds of local development, *i.e.*, where one set of beds occupies a matter of some few yards in actual horizontal distance. Gently inclined beds traceable over several yards on the whole yield less mineral residue.

(e) Beds which lie in a general definite direction, *i.e.*, prevalent current, yield the greatest quantity of mineral residue, also the "basic suite" of the deposit; beds lying discordantly to that prevalent direction tend to be restricted in yield and frequently exhibit mineralogical abnormalities.

(f) Horizontal beds intercalated with inclined beds usually give mineral residues characteristic of the deposit as a whole.

(g) In æolian deposits current-bedding is liable to be much more confused and irregular in major direction than is the case with water-born deposits; consequently mineral distribution tends to be quite haphazard. Heavy mineral in these circumstances often congregates in pockets, representing the lee-side deposition in local dune-formation. In other words, where the beds give evidence of dune characters, as is often the case with æolian sands, the gentle inclinations are the planes with least heavy mineral, the steeper inclinations, especially towards the bottomset ends, being more profitable in this respect.

(h) Both current-bedding and ripple-marking developed in beds of geological age, tend to reproduce the same conditions of natural mineral concentration as are encountered in modern shore and æolian deposits, *i.e.*, the heavy mineral being naturally segregated from the lighter.

Transgression of Chronologic and Lithologic Planes. The theoretical progression of lithological facies laid down on a continental shelf is from coarse to fine material, the grade-size of the constituent particles decreasing with depth of water in which they are deposited. This conception normally assumes a static condition of the sea-floor. Frequently, however, oscillation, gradual upheaval or subsidence of the basin is manifest, with the result that the interpretation of the record of sedimentation from the subsequently consolidated deposits is apt to be erroneous if formulated on purely lithological grounds.

The transgression of time-planes, *i.e.*, successive phases of sedimentation or bedding planes, by lithologic planes, *i.e.*, successive facies of deposition, is a direct result of one or other of those movements operative during sedimentation, and the significance of this phenomenon has been discussed by Prof. P. G. H. Boswell.¹ In the case of subsidence, the vertical thickness of the deposits is accentuated, while in the case of elevation, the lateral or seaward spread of the detritus is increased. In both cases definite facies such as sands, silts and clays are in juxtaposition when traced from one time-plane to another, so that ultimately when the deposits are consolidated, the tendency is for them to be differentiated on lithological grounds as true bedding planes, which is obviously fallacious. *Fig. 162* will serve to make this clear.

In tracing the mineral assemblage characteristic of the clay facies, for example, a variation will tend to occur in the residues as each successive time-plane is traversed, so that lateral correlation of the clay will be a matter of considerable difficulty. If, however, comprehensive sampling of the sand and silt grades associated with the clay is carried out, careful observation will detect a mineral suite characteristic of and common to the sand, silt and clay components of each successive time-plane, and thus a clue afforded to the real state of affairs. It is essentially the tendency of an inherent mineral assemblage to persist throughout a definite phase of deposition (involving change of lithological facies with progressively deeper water), that makes possible a correct interpretation of the true sequence of events.

¹ P. G. H. Boswell, *Trans. Liverpool Biol. Soc.*, xxxv., 1921.

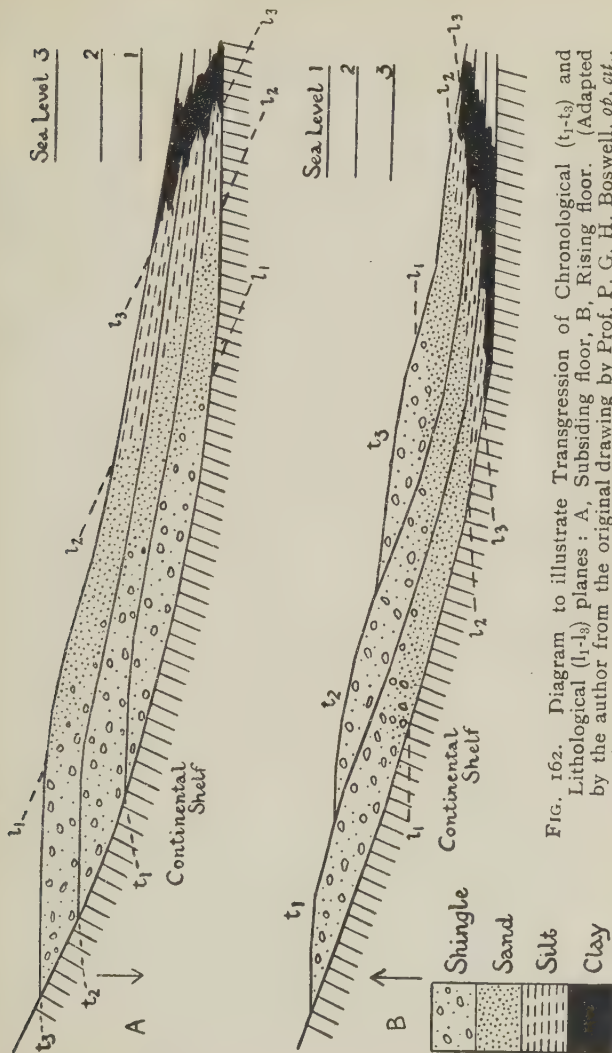


FIG. 162. Diagram to illustrate Transgression of Chronological (t_1 - t_3) and Lithological (l_1 - l_3) planes: A, Subsiding floor, B, Rising floor. (Adapted by the author from the original drawing by Prof. P. G. H. Boswell, *op. cit.*, p. 8.)

A concrete example of this transgression of time and lithologic planes is furnished by the Upper Lias—Lower Inferior Oolite Sands of the West of England. These sands occurring at different localities between the Dorset coast and the Cotteswold Hills have been proved by S. S. Buckman to vary in age from place to place, the time or specific ammonite planes transgressing the lithologic developments. Prof. Boswell deals with this lucidly in the paper cited, and with the relevant petrology in a more recent publication.¹

Similar complications may be anticipated in any sediments deposited under conditions in which oscillation of the basin has occurred concurrently with deposition, and examples are being constantly furnished during the course and geological development of various Tertiary oilfields in Asia and elsewhere.²

Impoverishment of Heavy Minerals. Sedimentary rocks which, from their lithologic character or circumstances of their origin, are deficient in heavy mineral, may present obvious difficulties in the application of these principles. In this category fall reconstituted sediments, very fine clays and most organic deposits.

Where sediments are composed chiefly of the “*remanié*” minerals of pre-existing sediments, both quantity and quality of accessory species are liable to suffer. The monotony of a uniform and restricted mineral suite, confined for the most part to such stable minerals as the iron-ores, tourmaline, zircon, garnet, etc., persistent through many hundreds of feet of strata, equally prevalent when the same rocks are followed out over large areas, renders subdivision on a petrographic basis very difficult, if not impossible in some cases. None but

¹ *Geol. Mag.*, lxi., 1924, pp. 246-264.

² L. D. Stamp, *Journ. Inst. Pet. Tech.*, xiii., 1927, pp. 21-52.

the broadest distinctions can be made, while comparison of samples from place to place, because of this constancy in composition, leads only to generalizations, not to definite criteria of equivalent horizons. Obviously there is little to be done in such circumstances; where the very indices on which we rely are lacking, other methods must be sought. On the other hand, these cases are, in the author's experience, the exception rather than the rule, and even in known reconstituted sediments such as the Wealden of England, differentiation within the formation is possible by means of heavy minerals (p. 419) and areal comparisons can be made with safety. In this instance it is attention to detail which matters.

With clays, given plenty of raw material to work upon, a reasonable amount of heavy mineral can usually be extracted, except from the very pure varieties. The trouble is obviated when dealing with outcropping rocks by the collection and treatment of large quantities of material; similarly with shales and other argillaceous types. It is when samples are meagre, as in the case of many oil-well samples, that the difficulty is intensified, and the utmost effort has to be made to obtain the maximum quantity of raw material which existing sampling apparatus can provide. In these days the advent of the core-barrel has done much to overcome this difficulty.

Limestones and similar organic rocks yield heavy mineral in proportion to their impurity; the purest types, *e.g.*, chalk, are notoriously sparse in detrital constituents. In such cases recourse must be made to the acid solubility factor as a basis of correlation (p. 106), though it is seldom that such rocks are not amenable to treatment by the more precise palæontological methods.

In the matter of saline deposits, including gypsum, etc., research has shown that detrital mineral constituents are in a few cases recoverable and can be used with advantage; also types of mineral crystallization are frequently invaluable in this connexion and should be studied accordingly. Structures revealed from thin sections of these massive mineral deposits are often of definite value as indices of certain developments at particular horizons, and are accordingly admissible as evidence. This aspect of the interpretation of thin sections may now be reviewed.

THIN SECTION CORRELATION.

The advent of core-samples of compact rocks in subsurface work has enhanced the possibility of differentiating between samples or correlating them by means of a microscopical study of thin sections cut therefrom, more particularly in the case of argillaceous and calcareous rocks. Hitherto, even comminuted limestones have proved, in the absence of other evidence, difficult to study from well-samples, the usual method being a quantitative comparison of inorganic (detrital and authigenic) material segregated by solution of the organic mass in acid.

In many oilfields calcareous rocks are a feature of the productive zones; sometimes such rocks are sufficiently individualized and developed as to offer no occasion for doubtful recognition from one well to another; on the other hand, where the sequence is made up of alternating limestones with shales, etc., identification and differentiation of successive horizons may be a matter of considerable structural moment, though furnishing a problem in specific identification of no mean difficulty. It is here that the thin section, studied from a particular angle, may prove of considerable value.

Investigation of several different limestones, both British and foreign, leads to the emphasis of essential morphological differences between types, quite apart from mineralogical and palæontological variation. For instance, a shelly limestone (so-called) exhibits fragmental remains of the larger fossil shells of all kinds set in a definitely or indefinitely formed matrix, *e.g.*, calcareous mud associated with iron compounds, sand, argillaceous matter or even volcanic detritus: at all events a matrix rendered conspicuous by its contrast to the main fossil-fragments and by its particular design, whether uniform or haphazard. Without identifying the fossil remains themselves, or testing microchemically for the type of carbonate composing them, an examination of the relationship of the larger to the finer constituents, *i.e.*, the fundamental structure of the rock, may lead to recognition of certain morphological characters common to that rock within a limited lateral and vertical development. With a compact limestone in which no large organic components are apparent, the nature of the calcite or dolomite mosaic, the degree of crystallization achieved or, alternatively, of mutual interference between the crystals, the manner of dissemination of secondary silica or iron compounds, and so on, may determine individuality whereby a particular example may be recognized. Oolitic, pisolitic and other special types of limestone may also be investigated from this point of view. Where the organic remains present can be identified, *e.g.*, *algal*, *foraminiferal*, *polyzoan*, *bryozoan*, coral and other types, obviously the possibility of linking up similar samples is still further enhanced (p. 310).

Similarly with shales, often the micro-organic (animal or vegetable) structures present may char-

acterize a rock as much by their mode of occurrence as by their nature; the uniformity of certain diatomaceous shales, the relationship of vegetal spores to lamination, etc., are two instances which may be quoted. Or, quite apart from the organic constituents, the essential structures of these rocks, *i.e.*, the degree of parallelism of their component elements, the development of incipient or obvious slaty cleavage, the spherical, elliptical or irregular shape of the coarser (usually quartz) elements, all these may bear comparison from sample to sample, from which identity may be established and correlation rendered possible.

It is not for one moment contended that this line of enquiry *always* leads to precise conclusions or that the method is infallible; but thin section analysis of core-samples is increasing in favour, and this particular bias of what is only, after all, an intensive study of consolidated rocks according to well-established petrological principles, clearly has merits where no other means of correlating such types are available; it should also be remembered that with argillaceous rocks especially, heavy mineral concentrates of sufficient bulk to make their use practicable in subsurface correlation, can only be obtained by treating large quantities of material, and this takes time; even then, the results are not always satisfactory.

The prime essential for this technique is a *really thin section*; this observation may seem somewhat trite, but the author has on more than one occasion been presented with problems whose solution was destined to rest on sections containing quartz of vivid interference colours. Admittedly certain sedimentary rocks are extremely difficult to cut very thin without losing important constituents or producing holes; since so much depends on

mutual relationship of components, holes at least must be reduced to a minimum. Fortunately skill comes with experience, and a good lapidary is seldom mastered, even by a rock-chip measuring less than half an inch square, a typical "cutting" from the bailer of a cable-tool drill (p. 14).

The essential petrology of consolidated rocks is dealt with in the previous chapter (VII) and is the basis of this particular work. As stated above, differentiation or correlation of samples by means of thin section rely primarily on composition and structure, both of which receive emphasis in that chapter. Given a good knowledge of the fundamental petrology, it requires relatively little practice to turn one's observations into comparative rather than the more usual descriptive channels, and this work is now a recognized part of the routine of almost every subsurface oilfield laboratory known to the author.

THE STUDY OF ACCESSORY MINERALS IN IGNEOUS ROCKS.

The investigation of isolated accessory minerals and heavy mineral assemblages is by no means limited to sedimentary deposits, as was shown some years ago by R. H. Rastall and W. H. Wilcockson in their work on Lake District granites,¹ more recently and exhaustively by A. Brammall and H. F. Harwood in connexion with the Dartmoor granite.¹ This latter research has specially served as an inspiration to many new workers in this profitable field.

Reference has elsewhere been made to methods of segregating accessory minerals from crushed rocks of whatever character (p. 73). Here

¹ See Bibliography, p. 497.

we have to note rather their significance and application in modern comprehensive studies of plutonic and associated igneous rocks, an application which parallels closely the technique with which this volume is largely concerned.

In thin section, accessory minerals, save the most prominent and common species such as apatite, zircon and iron-ores, normally escape detection, partly owing to their comparative scarcity with reference to essential rock-forming minerals, partly owing to their small size. Even high magnification, though it may serve to reveal many different individuals, does not offer the fullest facilities of study and diagnosis of these minerals *in thin section* of the rock as a whole, as it does when loose grains or carefully prepared concentrates are studied according to the principles laid down in this volume. Further, in the course of geochemical investigations of such accessory minerals, various physical and chemical tests, apart from those determinations ordinarily made with the petrological microscope, are necessary to their understanding, and obviously cannot be accomplished so long as they are components of consolidated rocks.

The work on the Dartmoor Granite has yielded abundant evidence of the value attaching to an intensive study of such accessory minerals. It has shown the existence of a rich and varied collection of species, many of which were previously not known to occur in that rock; it has stressed and proved conclusively the significance of varietal characters of these minerals, and has thus been the direct means of focussing attention on mineral vagaries so often passed by as adventitious or unimportant. The wider investigations, combining both field and laboratory observations, have shown

that particular accessory mineral assemblages may be characteristic of certain "stages" of intrusion or consolidation, or of specific developments and modifications of the normal rock, thus materially aiding correlation or differentiation of types. Their potentiality extends also to geochemical data with which petrogenetic problems are intimately bound up. Thus has a new scope of enquiry been instituted, a comprehensive technique established, which neither igneous nor sedimentary petrologist can afford to ignore.

Recognition of progress along these lines is attested by the number of papers which have since appeared dealing with problems and investigations similar to those defined and solved in connexion with the Dartmoor Granite. Among these may be cited the work of M. Chatterjee on the Western Bodmin Moor Granite, of P. K. Ghosh on the eastern part of the Bodmin Moor Granite, of A. W. Groves on the plutonic rocks of the Channel Islands, of D. R. Grantham on the Shap Granite, etc., of J. G. C. Leech on the St. Austell Granite, contributions to our knowledge of certain minerals in Scotch granites by W. Mackie, and the researches of F. Smithson on the granite and contiguous rocks of Ballycorus district, Dublin.¹

It may be safely assumed that few investigators of igneous rocks according to strictly modern principles will be content to describe their field-types merely from thin section in future, and accessory minerals will receive that degree of attention which their importance unquestionably merits. It is equally clear that detrital minerals, considered primarily as accessory constituents of igneous rocks, and thus studied "at the source" are made

¹ See Bibliography.

doubly potent in the solution of problems which seek to harmonize igneous and sedimentary activities at different geological epochs. Only by such thorough investigation of parent-rock and contributed sediment, can the full significance of any particular cycle of sedimentation be grasped.

CHAPTER IX.

SOME EXAMPLES OF DIFFERENTIATION AND CORRELATION OF SEDIMENTS BY PETROGRAPHIC METHODS.

Examples of Subsurface Stratigraphical Differentiation and Correlation in the Oilfields of S. California, Texas, Oklahoma, Rumania, Galicia—Area (Surface) Correlation illustrated by Cretaceous and Tertiary Rocks of England — Regional work in California — The Correlation of “Outliers.”

The principles and practice of “heavy mineral correlation,” as it has come to be known, have been sufficiently discussed in the last chapter, and are generally appreciated by workers on clastic sediments. There are some, however, who though conversant with the principles, have expressed a desire for a more detailed exposition of actual examples, either carried out on a series of subsurface samples, as under oilfield conditions, or on a series taken from outcropping rocks. There is, in point of fact, no material difference in technique in either case, excepting as already noted in the methods of treatment of the samples; it is true that with outcropping rocks there is often some field-evidence available as a guide to interpretation and conclusion, which evidence may be, and frequently is, altogether lacking with well-samples.

It is not an easy matter to give a written demonstration of the petrographic criteria involved in the differentiation of samples, since so much depends on actual microscopical examination of their residues, on comparison of individual and

collective properties of the mineral suites as previously described, and on what one may term "intuitive selection," *i.e.*, ability to group similar assemblages and to segregate dissimilar assemblages, chiefly a matter of experience. An endeavour is made, however, in the following paragraphs to convey to the reader the essential factors in the work by reference to a few of the many cases now worked out by different petrographers, including the author, in the hope that these examples and some accompanying photomicrographic illustrations may together afford assistance to those engaged for the first time on work of this character. The selection of examples has been chosen to cover most possible cases from subsurface stratigraphy to regional and local field-developments.

CASE I. OIL-SAND DIFFERENTIATION.¹ A series of core- and bit-samples from producing horizons penetrated by certain wells at depths from 3,500' to 4,800' below surface on the Santa Fe Springs field, Los Angeles basin, Southern California, U.S.A.

*Casual Grouping.*² Into two groups, one characterized by abundant and striking dark green hornblende, the other by epidote, biotite, pyroxene and *no* hornblende.

Detailed Analysis. The initial grouping into two dissimilar lots is confirmed by the following determinations of the essential constituents:—

Group 1. Residue plentiful, uniform grade, angular:—leucoxene (7),³ green and brown biotite (6), yellow epidote (6), pyroxene and zircon (5), colourless garnet (4), zoisite (3); noteworthy rarity of tourmaline. (*Fig.* 163, *Pl.* xxxvi.).

Group 2. Residue plentiful, mixed grade, sub-angular:—conspicuous dark green hornblende (8), pale greenish-yellow augite (6), pink garnet (5), green and brown

¹ Author's analysis.

² This has reference to the first segregations of dissimilar "slides" resulting from the preliminary "run-through" (p. 379).

³ Conventional expression of frequency (p. 386).

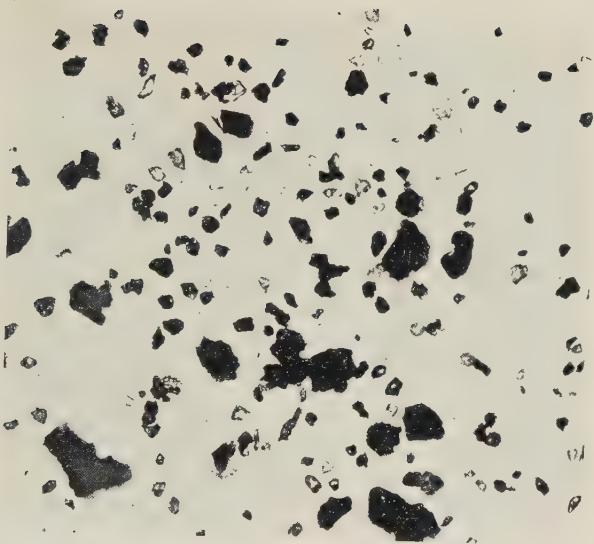


FIG. 163.

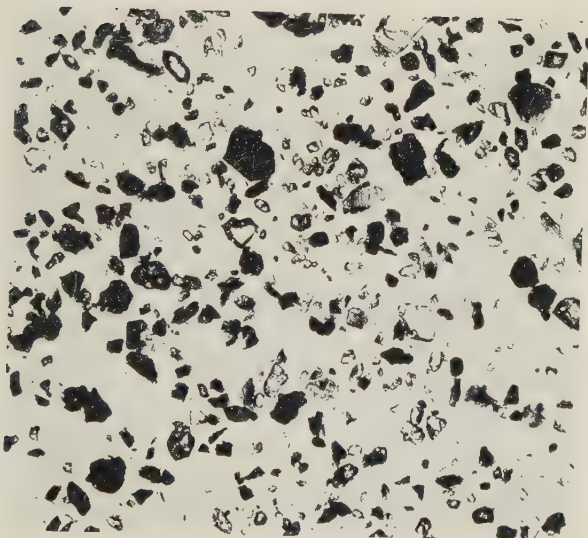


FIG. 164.

FIG. 163. "Bell Sand," Santa Fe Springs, Calif., U.S.A. [x 25.]

FIG. 164. "Meyer Sand," Santa Fe Springs, Calif., U.S.A. [x 25.]

To face page 412.

PLATE XXXVI.

biotite (5), leucoxene (4), epidote and zircon (4), white mica (occasional lepidolite) (3); noteworthy rarity of tourmaline. (Fig. 164, Pl. xxxvi).

Group 1, according to the depths recorded on the slides, characterizes a zone between 3,500' and 3,850'; the residues of this group are all very similar and no subdivision is possible. (This is the "Bell" or upper oil-zone of the field).

Group 2 characterizes a zone below 3,980' down to 4,800' in some samples investigated; the residues in this group are fundamentally similar, but there is a gradual and progressive change in the relative frequency of hornblende and garnet with depth of sample, deeper samples yielding more garnet than the shallower ones. (This is the famous "Meyer Sand," the main oil-producing horizon of this field).

Thus the mineral suites characteristic of Groups 1 and 2 respectively are quite different as seen under the microscope, hence samples from the two horizons are easily separated and correlation of each zone from well to well established.

CASE II. OIL-SAND DIFFERENTIATION.¹ A series of core-samples from two wells close together, from producing horizons of the Huntington Beach field, Los Angeles basin, California, U.S.A. The samples are from depths between 2,780' and 4,850'.

Casual Grouping. Into two groups, one characterized by a flood of pyrite, with muscovite, tourmaline and garnet; the other by much less pyrite, much zircon and abundant large, angular pink garnets.

Detailed Analysis. The casual grouping is sustained, but a transitional group between the two main groups is separable as follows:—

Group 1. Abundant residue, somewhat angular; composed chiefly of a flood of angular pyrite, often attached to quartz; muscovite (6), prismatic tourmaline (3), irregular, colourless garnet (5) and zircon (3). (Fig. 165, Pl. xxxvii.).

Group 2. Abundant residue, subangular; diminishing pyrite, other opaque minerals appearing; pyrite (6), prismatic tourmaline (4), pink garnet, ilmenite and zircon (2).

Group 3. Coarse, angular residue, mixed grade; a little pyrite. Pink garnet (8), zircon (6), tourmaline (4), ilmenite and leucoxene (4), titanite (3), muscovite (2). (Fig. 166, Pl. xxxvii.).

¹ Author's analysis.

Group 1, according to the recorded depths of the samples, characterizes a zone between 2,780' and 3,240'; this is known as the "Bolsa Zone."

Group 3 characterizes a distinctly different and deeper horizon (between 3,500' and 4,850') known as the "Ashton Zone."

Group 2 characterizes a transitional zone between the two in which the diminishing pyrite and gradual enrichment of the residue by other species are observed.

Thus the upper "Bolsa" and lower "Ashton" zones are clearly differentiated, and no difficulty is occasioned in separating samples from both, though the extent of the transitional zone might be hard to determine. The lithological evidence of the samples supports the petrographical analysis, those of the "Bolsa" being chiefly sandy shale or mudstone, from which a pyritous and somewhat restricted mineral residue would be expected, the samples from the transitional zone being more arenaceous, while those from the deep horizon are mainly coarse sandstones from which a rich mineral suite might reasonably be anticipated.

CASE III. THE COMPREHENSIVE ANALYSIS OF A PRODUCING OIL-SAND.¹ The chief diagnostic characteristics of one of the Middle Oligocene producing oil-sands at Goose Creek, Texas, U.S.A. (Average of three samples).

The samples were obtained from about 2,200' below surface, and were submitted to simultaneous micro-organic and petrographic analysis from which the following results were obtained:—

Lithology. Fine, angular sand, somewhat calcareous, with appreciable amount of clay and conspicuous fossil-shell fragments; of the latter, nothing determinate.

*Micropalæontology.*² Species of *Textulariidae*, *Globigerinidae*, *Rotaliidae* and *Nummulitidae* present; a good foraminiferal assemblage.

Petrography. The essential minerals include quartz, calcite, pyrite and glauconite. Pyrite was removed (p. 65)

¹ Author's analysis.

² For precise micropalæontological data see paper by E. R. Applin, A. E. Ellisor and H. T. Kniker, *Subsurface Stratigraphy of the Coastal Plain of Texas and Louisiana*; *Bull. Amer. Assoc. Pet. Geol.*, ix., 1925, pp. 79-122.



FIG. 165.

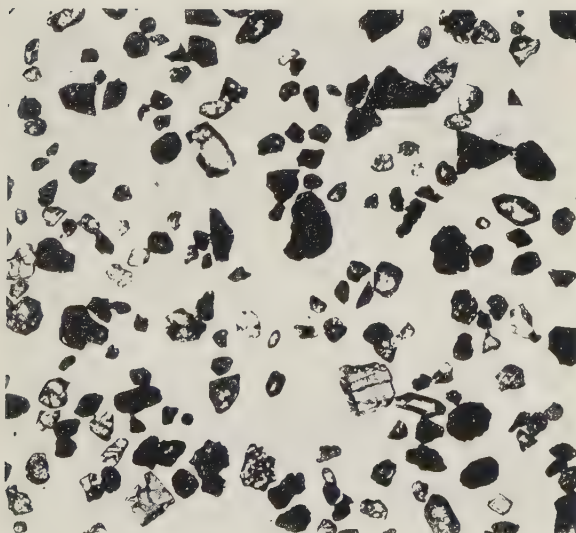


FIG. 166.

FIG. 165. "Bolsa Zone," Huntington Beach, Calif., U.S.A. [x 25.]

FIG. 166. "Ashton Zone," Huntington Beach, Calif., U.S.A. [x 25.]



FIG. 167.



FIG. 168.

FIG. 167. Oil Sand (Mid. Oligocene) Goose Creek, Texas, U.S.A. [x 25.]

FIG. 168. Oil Sand (Mæotic), Moreni, Roumania. [x 25.]

To face page 415.

PLATE XXXVI

and the heavy mineral suite isolated:—ample and characteristic residue, subangular grains; ilmenite and leucoxene (7), tourmaline, garnet, zircon and muscovite (5), kyanite (3), topaz (3), magnetite (3), staurolite (2). (Fig. 167, Pl. xxxviii.).

Thus the nature of the organic assemblage and the characteristic heavy mineral suite render this particular oil-sand clearly identifiable wherever met with, and on such evidence correlation of samples from this horizon from well to well is rendered possible.

CASE IV. OILFIELD STRATIGRAPHY: PETROGRAPHICAL DIFFERENTIATION OF "STAGES" AND FORMATIONS. The following example illustrates the heavy mineral residue differentiation of recognized palæontological stages and certain principal subdivisions of the Tertiary sequence of the Rumanian Oilfields (Carpathian Foothills). The formations represented are the Pliocene, Miocene and Eocene; the stages represented are the Levantine, Dacian and Mæotic (Pliocene), and the Sarmatian (Upper Miocene), all, among others, critical horizons in this geologically complex region.¹ The series of samples investigated (with the exception of the Eocene) mainly relate to the rocks of the Campina and Moreni districts.

*Petrographic Analysis.*²

Levantine. Abundant and varied mineral suite; angular; mixed grade, 0.1 mm. to 0.25 mm. Conspicuous feature: abundant angular, colourless garnet.

Assemblage constituted as follows:—colourless garnet (8), brownish-green tourmaline (6), yellow staurolite (5), leucoxene (including ilmenite) (5), rutile and zircon (4), muscovite, blue-green hornblende and epidote (3), kyanite (2), enstatite and blue corundum (sapphire) (1). (Fig. 169, Pl. xxxix.).

Middle Dacian. Abundant residue, less varied than that of the Levantine; angular; uniform in grade, 0.15

¹ For relevant geological details, reference should be made to two excellent papers, one by Lieut. G. C. Flower, R.N.R., F.G.S. (*Journ. Inst. Pet. Tech.*, xi., 1925, pp. 61-75), to whom, among others, the author is specially indebted for many of the samples above described; the other by J. Slomnicki, A.R.S.M., F.G.S., and E. Meyer, *Mining Mag.*, xxxii.; 1925, pp. 265-270.

² Author's analysis.

mm. to 0.2 mm., except for the large brownish-green, prismatic hornblende (0.25 mm. to 0.3 mm.), the conspicuous feature of the suite.

Assemblage constituted as follows:—prismatic brownish-green hornblende (7), small colourless, angular garnet (5), rutile and tourmaline (4), iron-stained leucoxene (5), muscovite and kyanite (3), staurolite (2). (*Fig. 17, Pl. xxxix.*).

Lower Dacian. Abundant residue, somewhat similar to that of the Middle Dacian, but more uniform in grade (0.25 mm. to 0.3 mm.) and rather more hornblende and garnet relatively to the associated minerals, than in the suite.

Assemblage constituted as follows:—dark green hornblende (8), angular, colourless garnet (3), leucoxene and ilmenite (4), zircon and muscovite (4), tourmaline, rutile and staurolite (3). (*Fig. 171, Pl. xxxix.*).

Mæotic. A distinctive and plentiful mineral suite, angular, very mixed in grade, but tending to be small (average 0.1 mm.).

Assemblage constituted as follows:—colourless, small angular garnet (7), leucoxene (including ilmenite) and green hornblende (5), equi-proportional occurrences of yellow staurolite, brown tourmaline, worn zircon and white mica (4), with accessory rutile (3). (*Fig. 172, Pl. xxxix.*).

Sarmatian. A very rich, uniform, fine grade residue (0.1 mm.), quite different in character from the preceding suites. Conspicuous feature is the variety of mica present.

Assemblage constituted as follows:—leucoxene (including ilmenite) (8), garnet (7), muscovite (large flakes, up to 0.35 mm.) (6), green mica (3), greenish-brown biotite (3), tourmaline, epidote, zircon and rutile (5), staurolite (3), glaucophane (2), yellow zircon, kyanite and green hornblende (1). [N.B.—Note impoverishment of hornblende compared with preceding suites.] (*Fig. 173, Pl. xxxix.*).

Middle Eocene (Moldavia). Not quite such a prolific yield of heavy minerals as with the other samples, but the suite is again distinctive, the characteristic features being the abundant rutile and zircon and the mixed grade of the residue.

Assemblage constituted as follows:—leucoxene (7), dark brownish-yellow rutile (7), two different types of zircon, large rounded prismatic grains and small fractured grains (together 7), garnet and tourmaline (4), muscovite and staurolite (3), titanite (1). [N.B.—Note absence of

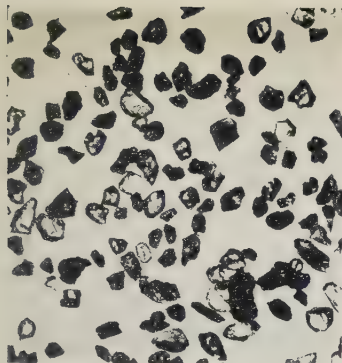


FIG. 169.



FIG. 170.

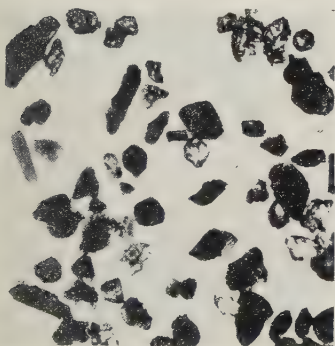


FIG. 171.

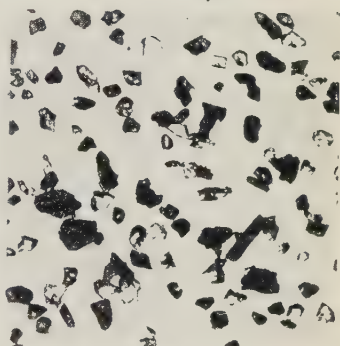


FIG. 172.



FIG. 173.

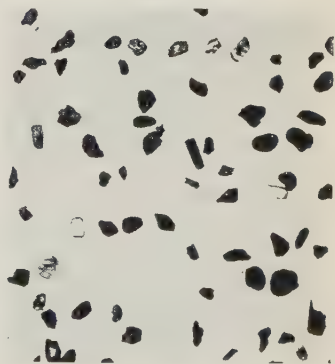


FIG. 174.

HEAVY RESIDUES FROM TERTIARY ROCKS, ROUMANIA. [All x 25.]

FIG. 169. "Levantine."

FIG. 170. "Middle Dacian."

FIG. 171. "Lower Dacian."

FIG. 172. "Maëotic."

FIG. 173. "Sarmatian."

FIG. 174. "Middle Eocene."

kyanite, hornblende and epidote characteristic of some of the above samples and horizons.] (*Fig. 174, Pl. xxxix.*).

Thus, not only are the heavy mineral suites yielded by samples from the Pliocene, Miocene and Eocene formations distinctive and accordingly separable, but in the case of the Pliocene, three of the four recognized stages are differentiated (Pontic material not available for study), and further, in that of the Dacian, the very rich oil-bearing horizon, middle and lower subdivisions are recognizable.

CASE V. STRATIGRAPHICAL IDENTITY OF PRODUCING OIL-SAND.¹ Some oil-saturated sands from wells on the Moreni field, Rumania. Determination of the producing horizon. The oil and petroleum residue had to be extracted with chloroform at the outset.

Casual Grouping. All mineral residues similar in this series, no subdivision possible.

Detailed Analysis. The quantity of residue varies somewhat with the samples, but mineralogical composition and physical characters are constant. Suite as follows:—leucoxene (including ilmenite) (6), angular colourless garnet (6), zircon (5), yellow staurolite, brown tourmaline and muscovite (4), kyanite (1). (*Fig. 168, Pl. xxxviii.*).

The minerals tend to be small in grade, about 0.15 mm., and the residue as a whole compares very favourably with that obtained from the Mæotic samples described under Case IV above. It lacks the distinctive greenish-brown hornblende characteristic of the Dacian samples, while its general appearance indicates that it bears no relationship to the rocks of that horizon. Hence the Mæotic horizon of these oil-sands is concluded.²

CASE VI. FORMATIONS DIFFERENTIATED BY INDEX-MINERALS. H. R. Lovely and F. P. C. Feilman have described an interesting example of petrographic differentiation of two important formations, *viz.*, the Wygoda Sandstone (Eocene) and the Jamna Sandstone (Eocene-Cretaceous) of the oilfield region of Boryslaw, Galicia.³ The distinction between the two formations is based in each case on one mineral species, *kyanite* as typical of the

¹ Author's analysis.

² For relevant geological detail, see paper by J. Slomnicki & E. Meyer, *Mining Mag.*, xxxii., 1925, p. 269.

³ *Journ. Inst. Pet. Tech.*, xi., 1925, p. 593.

Wygoda Sandstone, and *epidote* characteristic of the Jamna Sandstone, but absent in the Wygoda; otherwise samples of the deposits contain ilmenite, tourmaline, zircon, garnet, rutile and staurolite common to both, and in some instances the respective mineral suites show much morphological resemblance.

CASE VII. CORRELATION OF OIL-SANDS BY EXHAUSTIVE INVESTIGATION OF THE PHYSICAL PROPERTIES OF THE COMPONENT MINERALS. A. C. Trowbridge and M. E. Mortimore have contributed a paper on the correlation of four well-known producing sands, the Wilcox, Hominy, Bartlesville and Elgin, of N.E. Oklahoma, Mid-Continent Oilfield, U.S.A.¹

Their thesis is interesting on account of the stress laid on the physical properties (size and shape) rather than on the nature of the mineral constituents of the sands, also for the methods the authors adopt for recording "mechanical, shape and mineral analysis results," *i.e.*, by means of graphical representations.

The work is comprehensive and practically amounts to an intensive study of the sediments considered mainly from the lithologic standpoint, though micro-organisms as well as certain accessory heavy minerals are utilized. The graphical representations and charts are supported by photomicrographic illustrations to emphasize the features of dissimilarity between the samples of these sands.

In the case of the four sands and an "unknown" investigated, the data relied on for differentiation and correlation included fossils, degree of angularity and/or rounding of the constituent grains, shale fragments where present, chlorite, muscovite, magnetite, pyrite and pyrite crystals, quartz in greater quantity than 90%, zircon crystals, angular zircon, rounded zircon, tourmaline crystals, angular tourmaline, rounded tourmaline; the results may be summarized as follows:—

Wilcox Sand. Grade: well sorted, 55% to 75%, $\frac{1}{4}$ / $\frac{1}{8}$ mm.; shape: angular, subangular and fairly well rounded grains in equal proportions; no rock-fragments; minerals: muscovite absent, magnetite rare to common, pyrite rare, rounded tourmaline common, more than 90% quartz; practically unfossiliferous.

Hominy Sand. Grade: fairly well sorted, 40% to 65%, $\frac{1}{4}$ / $\frac{1}{8}$ mm.; coarser than the Wilcox. Shape: large well

¹ *Econ. Geol.*, xx: 1925, pp 403-423.

rounded grains; rock-fragments: green shale; minerals: muscovite absent, magnetite variable, crystallized pyrite common, tourmaline angular and well rounded; fossils: limited but recognizable microfauna.

Bartlesville Sand. Grade: not well sorted; shape: angular grains predominate, small percentage of fairly well rounded grains; no rock-fragments; minerals: muscovite rare or common, magnetite rare, tourmaline and zircon rare in crystals, chlorite present; practically unfossiliferous.

Elgin Sand. Grade: not well sorted; shape: angular grains predominate; no rock-fragments; minerals: zircon and tourmaline common in crystals, angular and sub-angular grains; unfossiliferous.

Thus it is seen that the identification of accessory heavy minerals is only incidental to the scope of the whole analysis, which depends in the main on the cumulative evidence of mechanical properties; the authors conclude "it is possible to differentiate these four sands by physical characters alone"; they note, however, "certain geographic and geologic limitations to the application of the methods. . . ." and "universal application is not claimed."

The comment may be made that this work stresses the significance of constancy or inconstancy of mineralogical properties, including physical criteria in petrographic work. But relying entirely on physical data necessitates quantitative determinations if the results are to have real correlative value, and where time is an essential factor, this may be impracticable; in any case, the limitations are probably narrower than when heavy mineral assemblages are used as the governing elements of differentiation, since physical properties of sediments are prone to much more rapid variation than accessory mineral constituents.

CASE VIII. STRATIGRAPHICAL DIFFERENTIATION (FIELD-OUTCROPS). From time to time the author has published accounts of the value of petrographic methods in the geology of the Weald of S.E. England, where the deposits are for the most part exceedingly variable lithologically, and where palæontological evidence is often meagre or entirely lacking. Work in the East Grinstead district illustrates this application.¹ In this case nearly 200 samples were collected and investigated from outcropping rocks in an

¹ H. B. Milner, *Proc. Geol. Assoc.*, xxxiv., 1923, pp. 283-300.

SUMMARY OF PETROGRAPHIC CHARACTERS OF THE WEALDEN BEDS, GRINSTEAD AREA, SUSSEX.

LOWER CRETACEOUS						
Horizon	No. of Samples	Lithology	Grade	Percentage "Heavy" Residue (by Weight)	Character of Minerals	Heavy Mineral Composition (in Order of Frequency)
Upper Tunbridge Wells Sand	20	Sandstone	0.01—0.1 mm.	0.22	Subangular	Leucoxene (8), Zircon (8), Rutile (7), Tourmaline (6), Brookite (4), Anatase (3).
Grinstead Clay Pebble Bed	5	Clay with Sandstone Pebbles	Matrix: < 0.01 mm. Pebbles: $\frac{1}{2}$ cm.—2 cm.	—	Pebbles Rounded	Leucoxene, Muscovite, Tourmaline, Rutile, Zircon.
Grinstead Clay	10	Mottled Clay	0.01 & < 0.01 mm.	Approx. 0.02	Irregular	Limonite (after hæmatite), Muscovite, Tourmaline, Zircon
Lower Tunbridge Wells Sand : Conglomerate	16	Pebbles in Sandy Matrix	Pebbles : > 2 mm. Matrix : 0.3—0.5 mm.	—	Pebbles Subangular Matrix Angular	Leucoxene (8), Zircon (7), Tourmaline (5), Garnet (5), Rutile (4), Ilmenite (3), Staurolite (2), Hornblende (2), Brookite (2), Monazite (2).
Lower Tunbridge Wells Sand	68	Calcareous Sandstone	0.07—0.25 mm.	0.20	Water-worn Subangular	Leucoxene (8), Tourmaline (7), Zircon (6), Ilmenite (5), Rutile (5), Magnetite (3), Staurolite (3), Hornblende (3), Brookite (2), Anatase (2).
Wadhurst Clay	5	Clay	0.01 & < 0.01 mm.	0.03	Irregular	Pyrite, Zircon, Muscovite.
Ashdown Sand	55	Sandstone Silt	0.05—0.1 mm.	0.01— 0.05	Subangular	Muscovite, Leucoxene (8), Zircon (7), Tourmaline (6), Rutile (5), Ilmenite (4), Magnetite (2), Staurolite, Brookite and Anatase sporadic.

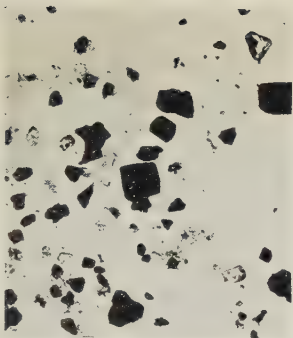


FIG.
175.



FIG.
176.

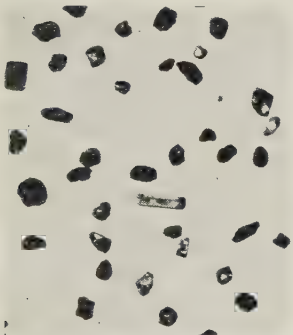


FIG.
177.

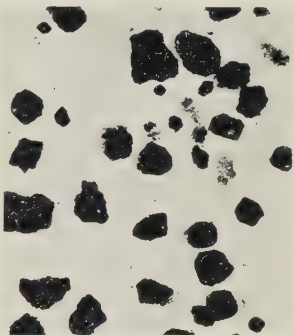


FIG.
178.



FIG.
179.



FIG.
180.

- HEAVY RESIDUES, WEALDEN (LOWER CRETACEOUS), S.E. ENGLAND. [All x 25.]
- Fig. 175. Weald Clay (*Pyrile*, *Muscovite*, *Tourmaline*, *Zircon*, *Kyanite*, etc.), Groombridge, Sussex.
- Fig. 176. Up. Tunbridge Wells Sand (*Leucoxene*, *Zircon*, *Rutile*, *Tourmaline*, etc.), Tunbridge Wells, Kent.
- Fig. 177. Lt. Tunbridge Wells Sand (*Iron Ores*, *Leucoxene*, *Tourmaline*, *Zircon*, etc.), Ashurstwood, Sussex.
- Fig. 178. Wadhurst Clay (*Pyrile*, *Mica*, *Quartz with inclusions*, etc.), Cullinghurst Wood, E. Sussex.
- Fig. 179. Ashdown Sand (*Iron Ores*, *Leucoxene*, *Zircon*, *Tourmaline*, *Mica*, etc.), Fairlight, Sussex.
- Fig. 180. Fairlight Clay (*Spherulitic Siderite*, *Pyrile*, *Garnet*, etc.), Fairlight, Sussex.

area of approximately 36 sq. miles, five different stratigraphical subdivisions being involved and two distinctive lithological developments. The results, for comparative purposes, may be summarized as in the accompanying table (p. 420).

It will be observed that there are significant differences in the amounts of mineral residue extracted from each member of the Lower Cretaceous series represented.

The *Upper Tunbridge Wells Sand* is essentially a zircon-rutile suite of distinctive character; the *Grinstead Clay* has a restricted muscovite-tourmaline-zircon suite, with absence of secondary pyrite (characteristic of the older *Wadhurst Clay*); the *Lower Tunbridge Wells Sand* yields a richer assemblage than the others, and zircon is usually subordinate to tourmaline in quantity; *Wadhurst Clay* is characterized by pyrite, mica, chlorite and zircon, while the *Ashdown Sand* gives a zircon-tourmaline-mica suite of fine, uniform grade, the first-mentioned mineral nearly always predominating.

Thus each subdivision is identifiable by reference to its particular mineral assemblage, taking into account not only the minerals themselves and their varying frequencies, but also the physical characteristics of each typical suite. For further petrographic work of a similar nature (involving Wealden rocks), see references cited below, where, also, some of the typical residues are further illustrated.¹ (Figs. 175-80, Pl. xl.).

CASE IX. STRATIGRAPHICAL DIFFERENTIATION (FIELD-OUTCROPS). S. W. Wooldridge has recently investigated the Bagshot Sands (Eocene) of Essex,² and in the course of the work has had occasion to draw attention to the striking lithological similarity between them and the older Oldhaven Sands, separated from each other by 400' to 500' of London Clay. He says: "Taken in bulk, the mineralogical contents of the two sands are similar. The differences which appear on closer inspection and which are, moreover, definite and significant, are as follows:—"

In the Oldhaven Beds:

(i.) *Kyanite* larger, better-formed and more abundant.

¹ H. B. Milner, *Proc. Geol. Assoc.*, xxxiv., 1923, p. 47; xxxv., 1924, pp. 383-394; also (with A. J. Bull) xxxvi., 1925, pp. 312-315.

² *Proc. Geol. Assoc.*, xxxv., 1924, pp. 359-383.

- (ii.) *Rutile*, deep red-brown in angular and rounded grains, larger than similar grains in the Essex Bagshot Sands.
- (iii.) *Zircon* much less abundant.
- (iv.) *Tourmaline*. Green and peach-coloured varieties commoner than in the Bagshot Beds. Also "squat brown prisms which are rare or absent in the latter."
- (v.) *Staurolite* is more abundant.
- (vi.) *Hornblende* characterized by bluish absorption tints suggesting the presence of the glaucophane molecule.
- (vii.) *Garnet* fairly common; rare or absent in newer Eocene.
- (viii.) Beds are less micaceous but more glauconitic.

Thus there is plenty of evidence available for distinguishing petrographically between the two formations, quite apart from field-data.

CASE X. STRATIGRAPHICAL DIFFERENTIATION IN CALIFORNIA, U.S.A. F. G. Tickel contributed a paper on "The Correlative Value of the Heavy Minerals" arising from his investigations of some Tertiary formations of part of West Ventura County and the region south of Coalinga, California.¹

He says: "In the region south of Coalinga . . . the Tejon (Eocene) beds can readily be differentiated, microscopically, from the overlying Miocene formations. The Miocene beds contain abundant minerals of the amphibole group, while the Eocene beds contain almost none." In the Fernando (Pliocene) of Ventura River, his work led to the detection of two zones, one characterized by glaucophane and green amphibole, the other by epidote. He concludes: "Study of the heavy minerals constitutes a valuable aid in the correlation of oilfield formations, supplementing and verifying the evidence of the microscopic fossils, or filling the gap where fossils are not found. Mineral grains are not destroyed by the drill; well-samples are just as suitable for study as outcrop samples, and, of course, core-barrel samples offer the best material of all. Much significant information would be obtained by their systematic microscopic study."

¹ *Bull. Amer. Assoc. Pet. Geol.*, viii., 1924, pp. 158-168.

CASE XI. A FURTHER CALIFORNIAN EXAMPLE. R. D. Reed has contributed a critical article on the "Role of Heavy Minerals in the Coalinga Tertiary Formations," wherein he discusses the restrictions, advantages and disadvantages of heavy minerals in correlation.¹ His investigation included typical material from the following horizons:—Avenal (Eocene), Kreyenhagen (Oligocene?), Temblor (Miocene), Santa Margarita (Miocene), Etchegoin (Pliocene) and Tulare (Pliocene).

He states "Between the Miocene and Pliocene formations of the Coalinga district no persistent differences in heavy mineral content have been discovered. As already suggested, however, any sample of the Avenal sandstone . . . can readily be distinguished by a mere glance at its heavy minerals, from a sample of any of the Miocene or Pliocene formations. There is no reason to doubt that similar differences may be found elsewhere between otherwise similar formations." "Finally, there is some reason to believe that heavy mineral zones, at least in the California Tertiary formations, are in general thinner than most fossil zones."

While the present author does not agree with certain of the views expressed in this paper, Reed has clearly established the mineralogical indices of rocks which are not always easily identifiable by other means.

CASE XII. CORRELATION OF OUTLIERS. S. W. Wooldridge and F. Gossling recently discovered two outliers of Lenham Beds (Pliocene) in Surrey, hitherto thought to be of much earlier Tertiary age.² No fossils were found in the beds in question, but their position (relative O.D.) and lithological and petrographical features, are comparable in all respects with similar outlying patches of known Pliocene material on the North Downs.

A comparison of the heavy residues from these beds with established Pliocene deposits (eastern facies) of similar horizon, leaves no room for doubt as to their Lenham character and affinities. The authors state, "the mineral suite is characterized by the very abundant andalusite, kyanite and staurolite; and by the constant presence of small amounts of monazite, sillimanite and green spinel. A negative character of some significance is the absence of garnet.

¹ *Econ. Geol.*, xix., 1924, pp. 730-749.

² *Proc. Geol. Assoc.*, xxxvii., 1926, pp. 92-101.

The suite thus defined agrees closely with that found by Mr. Davies in the more southerly outliers [Lenham, etc.], the only difference being due to a slight admixture of Eocene material " . . . " in view of the fact that the beds described occur in such a familiar locality and have been so long overlooked, it has been thought well to present the fullest possible evidence as to the age of the beds, and to emphasize their dissimilarity from the associated Eocene sediments."

For further examples of correlation based on heavy minerals, see references cited below.¹

The foregoing twelve examples are sufficiently varied as regards geographical and stratigraphical criteria, surface and subsurface occurrence, and in technique of investigation, to illustrate the applications of the petrology of sedimentary rocks to stratigraphical problems of all kinds, more especially those involving correlation of doubtful horizons. These samples will, it is hoped, suffice as a guide to similar work anywhere.

It cannot be too often stressed, however, that competence in diagnosis of detrital minerals and caution in this particular interpretation of their significance, are essentials if successful results are to be achieved; proficiency comes with continuous experience with all sorts and conditions of sediments; but the greater that experience, the more cautious the investigator becomes.

¹ H. B. Milner, *Q.J.G.S.*, lxxviii., 1922, pp. 348-377; P. G. H. Boswell, *Q.J.G.S.*, lxxix., 1923, pp. 205-230; R. D. Reed & J. P. Bailey, *Bull. Amer. Pet. Geol.*, xi., 1927, pp. 359-368; W. G. Shannon, *Proc. Geol. Assoc.*, xxxix., 1928, pp. 137-153; also *Geol. Mag.*, lxiv., 1927, pp. 145-153; W. F. Fleet, *Proc. Geol. Assoc.*, xxxviii., 1927, pp. 1-48; also *Geol. Mag.*, lxii., 1925, pp. 98-128.

CHAPTER X.

THE BEARING OF SEDIMENTARY PETROGRAPHY ON PALÆOGEOGRAPHICAL PROBLEMS.

Although for some purposes it may be sufficient simply to effect the qualitative and quantitative examination of a deposit, geologically speaking the investigation is incomplete without carrying the inquiry still further, *viz.*, to a consideration of the source or sources of origin of the material, and its bearing on the palæogeography of the area at the time of deposition. The perusal of this more philosophical aspect of the science is not merely academic; indeed, one might almost say that without such an inquiry all petrographic work must lose both in precision and value: it will certainly lack vitality. As an aid to problems of correlation on the lines discussed in Chapter VIII, such research is of fundamental importance.

Tracing the source of constituent particles of a deposit is often by no means a straightforward matter, especially where the locale of a distributive province capable of furnishing the material is obscure, or where, owing to widespread erosion, no direct evidence of such a province exists. The problems to be faced are, from their very nature, some of the most complex and absorbing that a geologist has to solve, and each case must perforce be dealt with on its own merits. Accordingly we cannot presume to do more than indicate here cer-

tain broad factors to be taken into account in all considerations of this character, leaving it to the initiative and ability of the investigator to evolve the more detailed plan likely to lead to the most reasonable conclusions in the particular case with which he is concerned.

The mineralogical analysis of a deposit will show a certain suite of detrital grains which may or may not be suggestive of the source of origin, either individually or collectively. Generally speaking, there is seldom an instance where the petrographer fails to gain some clue, however small, to the source of some at least of the species represented. In the descriptions of the detrital minerals given in Chapter VI, possible sources of origin of the several species are included to enable an initial estimate to be made; this information, however, only applies to individual grains. Paragenesis is just as important a factor in detrital sediments as in igneous or metamorphic rocks, and more often than not the indication of the source of origin of the deposits comes from the association of species noted, rather than from particular minerals.

The association of sillimanite, kyanite, andalusite and garnet, or again, a garnet-staurolite-kyanite suite, are both suggestive of derivation from a definite thermo-metamorphic province, just as a titanite, apatite and zircon assemblage (if marked) is indicative of acid or intermediate plutonic rock-types as possible sources of supply. The characteristic association of rhombic and monoclinic pyroxenes often with ceylonite and possibly serpentine (? after olivine) in addition, points to derivation from basic or ultrabasic rock-types, while the prevalence of cassiterite, topaz, white mica and rare-earth minerals in certain sands may be equally suggestive of their primary

environment. On the other hand, a predominance of the more stable minerals such as zircon, tourmaline, rutile and iron-ores, probably to the total exclusion of such other species as are mentioned above, implies derivation from pre-existing sediments, and in such cases the location of the ultimate source of origin may be rendered considerably more difficult.

Knowledge of likely mineral associations is also helpful in diagnosis. Paragenetic species not only suggest provenance, but imply certain "index" minerals anticipatory of related detritals for which the assemblage may profitably be searched. For instance, where diagnosis of a particular mineral proves difficult and a decision between two or more possibilities has to be made, the claim of the more likely species, deduced from the presence of "indices," often leads to positive identification. Examples of "index" minerals and the suites thus implied may be given:—

Olivine, magnetite, chromite, picotite, serpentine, ceylonite, rhombic and monoclinic pyroxenes.

Cassiterite, tourmaline, topaz, fluorite, apatite, muscovite, hypersthene.

Corundum, purple quartz, topaz, garnet, spinel, monazite, titanite, ? beryl, often with members of the sillimanite suite (below).

Sillimanite, kyanite, andalusite, chiastolite, staurolite, topaz, monazite, tourmaline, garnet, cordierite.

Diopside, rhombic and monoclinic pyroxenes, amphiboles, olivine.

Epidote, chlorite, zoisite, garnet, vesuvianite.

Axinite, tourmaline, hornblende, biotite, titanite, epidote, pyroxene.

Chloritoid, muscovite, biotite, tourmaline, titanite, garnet and quartz with abnormal interference colours (strain), pyrite, chlorite, graphite, corundum, spinel, rutile.

The "index" minerals are *italicised* in the above lists, but it is obvious that other species in

the suites may individually or collectively assume equal importance. Once a particular mineral association is established and its relationship to a definite source of origin inferred, confirmation of such provenance should be sought by appealing to significant varietal characters of the index-species. This implies, however, detailed knowledge of the parent-rocks themselves, quite apart from the sediments involved.

Investigations of provenance must take into account not only the heavy mineral evidence but also that arising from a study of the coarser constituents, *i.e.*, boulders, pebbles and rock-fragments of macroscopic size. Many examples of the significance of these components occur throughout the literature; we may cite A. Gilligan's investigations of the pebbles of the Millstone Grit of Yorkshire;¹ the late T. G. Bonney's work on the Bunter Pebble Beds of the Midlands;² and the Wealden deposits of S.E. England in which conglomerates developed at certain horizons contain pebbles of undoubted Jurassic origin, thus confirming other evidence as to the essentially sedimentary provenance of these rocks.³

In another direction, the investigation of the nature of inclusions in minerals, especially in quartz, frequently repays detailed study; this follows along the lines laid down by W. Mackie in the course of his work on various Scottish rocks;⁴ it is emphasized by Gilligan in his researches on the Millstone Grit referred to above, while more recently the significance of varietal features of and inclusions in certain prominent Dartmoor minerals

¹ *Q.J.G.S.*, lxxv., 1919, pp. 253-259.

² *Q.J.G.S.*, lvi., 1900, p. 287.

³ H. B. Milner, *Proc. Geol. Assoc.*, xxxiv., 1923, pp. 297-8.

⁴ *Trans. Edinburgh Geol. Soc.*, vii., 1896, p. 148.

has been discussed by A. Brammall in a masterly contribution to the subject of provenance.¹

Writing of the typical Dartmoor detrital assemblage, that author summarizes the evidence of "Dartmoor provenance" in terms so lucid as to rank them as first principles of far wider application. He says, "Individually the species enumerated . . . do no more than suggest the possibility of a Dartmoor provenance, but possibility might be strengthened to probability by coincidences based on (a) relative abundance, (b) varietal features, and (c) nature of inclusions. Whether probability could itself be strengthened to carry conviction would depend on the number of such coincidences. For example:—Zoned zircons alone are of little value as evidence of Dartmoor provenance. Their evidential value rises by virtue of inherent features (abundance, size, nature of inclusions, etc.), and of associations: if they are associated with clear zircons subordinate in amount and showing certain peculiarities, their value is enhanced, and this value rises progressively by association with octahedrite, tabular anatase, monazite, brookite, manganiferous garnet, etc., in varietal agreement with known Dartmoor species. Scrutiny of material along these lines implies the need for an exhaustive examination of material. . . ."² The importance of these observations is realized by all workers on sedimentary deposits to which the Dartmoor Granite and its associated rocks have been laid under contribution, as has been shown by A. W. Groves recently in connexion with the distribution of its detritus in S. England³. But the example is of universal

¹ *Proc. Geol. Assoc.*, xxxix., 1928, pp. 27-49.

² *Ibid.*, p. 47.

³ Paper in course of publication. *Abs. Proc. Geol. Soc.*, No. 1197, March 28, 1929.

significance and the principles implied underlie every investigation into the source of origin of sedimentary rocks.

It frequently happens that a particular mineral will, by its form, colour or other specific character, betray its source of origin from strong resemblance to the same species known to occur in older rocks; this is specially the case with younger sediments which have in part been derived from the breaking up of pre-existing detritus. In this way a flood of light may be thrown not only on the direction and mode of transport, but also on the physiographical conditions prevalent at the time of deposition. Thus the staurolite occurring in the Bunter Pebble Bed of South-West England has been traced to the Armorican massif (or its more northerly extension in Triassic times): hence is deduced the prevalent flow of sediment-bearing currents from the south.¹

The author's work on the Pliocene deposits of Cornwall has shown that the staurolite occurring in these has had the same derivation, while the presence of Lower Cretaceous types of kyanite in the most northerly localities has suggested the flow of sediment-bearing rivers from the north-east, *i.e.*, from the region in which, in Pliocene times, the main mass of Cretaceous rocks was extant.² Again, in view of W. Mackie's researches on the accessory minerals of Scottish granites in which he proved the occurrence of monazite in 43 out of 52 examples examined,³ the presence of this species in the Millstone Grit of Yorkshire is a strong argument in favour of the contention that that deposit had a northerly derivation.⁴

¹ *Q.J.G.S.*, lviii., 1902, p. 630.

² *Q.J.G.S.*, lxxviii., 1922, pp. 348-377.

³ In A. Gilligan, *Q.J.G.S.*, lxxv., 1919, pp. 271-2.

⁴ A. Gilligan, *op. cit.*

Recent work on the source of purple zircon in Scottish sedimentary rocks furnishes yet another instance of the significance of a particular variety of a mineral in connexion with problems of their origin.¹ In this case the provenance is the Lewisian Gneiss. By the same indication it has been shown that the Moine Series is older than the Torridonian and that the latter rocks owe their origin partly to the Archæan Gneisses and partly to the Moine Schists. In view of the fact that purple zircon is also widespread in many other sedimentary rocks in this country, being met with, for instance, in Eocene deposits as far south as Dorset, Devon and Cornwall, Prof. Boswell's recent contribution to the distribution of this variety is both interesting and suggestive.² In short, once the ultimate geological source is established of a mineral whose specific properties proclaim it an adequate indicator, it becomes *per se*, an invaluable guide not only in "placing" the distributive province, but also in reconstruction of the salient events with which the particular sediment or sediments have been concerned.

In working out problems of this nature, therefore, it is advisable firstly to note the possible types of rocks from which each mineral species may have been derived, and secondly to investigate the presence (or absence) of such types within a likely region capable of furnishing the material. In this way palæogeographical questions arise collaterally, and the unravelling of the geological record within the limits of the periods represented by both parent-rock and sedimentary deposit constitutes the crux of the whole matter.

¹ W. Mackie, *Trans. Edinburgh Geol. Soc.*, xi., 1923, pp. 200-213.

² *Mineralogical Mag.*, xxi., 1927, pp. 310-317.

Palæogeographical restoration, to be complete and accurate, necessitates a very detailed knowledge of regional stratigraphy and also the absence of imperfections in the geological record. The former may be acquired by the geologist as a result of detailed work—in fact its realization is a *sine quâ non* to the successful prosecution of all petrographic work. The latter is largely a matter of chance, and naturally varies in different districts. Obviously the more faithfully the history of past geological events is chronicled by the rocks, the more complete is the stratigraphical record, and solutions to problems of geographical reconstruction are facilitated accordingly. If, in this connexion, we compare south-east with south-west England, it is at once apparent that palæogeographical investigations in the former, where there are few gaps within the limiting series as developed, are much more straightforward than in the latter region, where no evidence whatever is preserved of the trend of events between late Palæozoic and early Tertiary times.

Again, the evidence of organic remains (where these are preserved) must obviously play a fundamental part in inquiries of this nature; only where palæontological investigations are followed hand-in-hand with petrographical analysis can we expect to gain the fullest knowledge, enabling each step in the process of reconstruction to be made with a reasonable degree of accuracy.

The bearing of certain detrital grains on questions concerning climatic conditions prevalent at the epoch of deposition has received a good deal of attention from various observers. Under certain conditions the evidence afforded is convincing, especially in the case of felspar grains, but frequently it must be admitted that the indications are

inconclusive. As early as 1886 Judd described the freshness of the felspar grains of the Nile deposits as indicative of mechanical disintegration and desert conditions, *i.e.*, tropical heat by day and rapid cooling by radiation at night.¹ Medlicott and Blandford,² of the Indian Geological Survey, have drawn attention to differentiation of altered and unaltered felspar grains, the former as indicative of mechanical attrition, the latter of chemical weathering; in this way felspar grains present in the Siwalik deposits and also in the Indo-Gangetic alluvium, are ascribed to the breaking down of the parent-rocks by ice and frost, since they are remarkably fresh and unaltered.

W. Mackie's paper "Felspars in Sedimentary Rocks as Indicators of Climate,"³ is another instance of detailed research in the differentiation of fresh and altered felspar grains as criteria of mode of attrition, hence of prevalent climatic conditions. Where alteration is very marked, the inference to be drawn is that moist and humid conditions prevailed, tending to promote chemical decay; where freshness of felspar is the marked feature, mechanical attrition under arid or glacial conditions is suggested, and in such cases a decision must be made between the one or the other by general stratigraphical and lithological evidence; the marked angularity of grain characteristic of glacial deposits, usually contrasts in a striking manner with the strong tendency to rounding exhibited by æolian detritus.

The conditions attendant on deposition of the Millstone Grit, indicate a prevalent monsoon type of climate, by which heavy rains, capable of feed-

¹ *Proc. Roy. Soc.*, xxxix., 1886, pp. 215, 217.

² *Manual of the Geology of India*, 2nd Ed., 1893, p. 201.

³ *Trans. Edinburgh Geol. Soc.*, 1898, p. 443.

ing large rivers, were maintained; hence the weathering of the material was preponderantly mechanical, as evidenced also by the character of the grains and particularly by the "exceeding freshness of the feldspars."¹

The more detailed study of detrital grains has served to show that not only feldspar, but also minerals like staurolite, andalusite and kyanite may be indirectly indicative of climatic conditions, partly from observations of their degree of alteration, and partly from considerations as to their ultimate origin. In the Pliocene deposits of Cornwall the staurolite grains preserve a subangularity entirely consistent with marine transport; their source of origin from the south-west is suggestive of prevalent currents from that direction, thus reflecting present-day conditions. Confirmatory evidence of this is to be found in the location of the Pliocene outlier at St. Agnes on the leeward side of St. Agnes Beacon (N.E.), and by comparison with prevailing climatic conditions of Cornwall to-day, where heavy rains are wont to accompany south-west winds, we may infer, with a reasonable degree of accuracy, somewhat similar conditions operative in early Pliocene times.²

The evidence afforded by andalusite is rather more obscure, but a study of the mineral shows that there are two distinct types of weathering, one characteristic of the species derived from contact metamorphic rocks, the other characteristic of grains derived from andalusite-bearing granites. In the former case the degree of alteration is usually far more advanced than in the latter instance; sericite, kaolinite and possibly chloritic matter may be so

¹ A. Gilligan, *op. cit.*

² H. B. Milner, *op. cit.*

prevalent as to cloud the grain entirely, particularly under climatic conditions favourable to intensive chemical weathering. This will, of course, to a certain extent, apply to grains derived from granitic rocks under similar conditions, but it is a noteworthy fact that where this source of the mineral is determined, its freshness and form are clearly indicative of mechanical disintegration, generally under rather frigid climatic conditions.

The investigation of the mineralogical constitution of sedimentary rocks has now proceeded far enough for the geochemical significance of commonly occurring detrital and authigenic species to be appreciated and discussed with a fair degree of accuracy. The cumulative evidence of the study of sediments of all types and geological ages impresses us with certain well-marked tendencies whereby definite minerals or groups of minerals become criteria of environmental conditions. This does not imply merely a potentiality of these minerals to indicate provenance or peculiar climatic conditions, but rather their role as indices of the varying natural influences, collectively determining the natural history and ultimate geological character of sedimentary formations.

Any special meaning attaching to the presence of some particular mineral or suite of minerals may be directly interpreted from them or may only be suggested when there are other terms of reference; thus a series of altered microcline grains may be accepted evidence of a humid environment of sedimentation, or glauconite may in the majority of cases be sufficient proof of a marine environment; but the reason or precise significance of the occurrence of apatite, barite or dolomite in a sediment may not be apparent until

full lithological and petrographical data are known.

The presence, as also the absence, of primary rock-forming minerals in sediments *ipso facto* raises questions of relative chemical and physical stability; the survival of certain species under one set of conditions, and their destruction under another, are alike provocative of further investigation leading to valuable stratigraphical conclusions; authigenic minerals may imply not only specific geochemical reactions, but may directly signify by the nature and achievement of such reactions, environmental conditions; in short, there is a wealth of natural history to be learnt from an intelligent interpretation of sedimentary rock-minerals, and it is the purpose of the remaining paragraphs of this chapter to summarize briefly significant data in this connexion. Apart from focussing attention on a theoretical aspect of the petrology of sediments, it is hoped that this contribution will, by creating yet another perspective, serve to stress once more the true aim and scope of all intensive petrographical research.

Preliminary to the annotation of the individual species, it is convenient to set out in tabular form certain tendencies observed from a broad survey of the minerals described in this work.

Mineral	Occ.	Stab.	Freq.	Mineral	Occ.	Stab.	Freq.
Actinolite	D	s	l	Hypersthene	D	s	r
Anatase	D & A	S	c	Ilmenite	D	s	c
Andalusite	D	s	l	Kaolinite	A	S	c
Anhydrite	A	s	l	Kyanite	D	S	c
Apatite	D	U	r	Lepidolite	D	S	vr
Aragonite	D & A	s	c	Leucoxene	A	S	c
Augite	D	s	l	Limonite	A	S	c
Axinite	D	s	vr	Magnetite	D	S	r
Barite	A	S	l	Marcasite	A	s	l
Biotite	D	s	c	Microcline	D	s	e
Brookite	A	S	r	Mohazite	D	S	r
Calcite	D & A	S	c	Muscovite	D & A	S	c
Cassiterite	D	S	l	Olivine	D	U	r
Celestite	A	s	l	Orthoclase	D	S	c
Ceylonite	D	s	r	Picotite	D	S	vr
Chalcedony	D & A	S	c	Plagioclase	D	s	l
Chiasolite	D	s	l	Pyrite	A	s	c
Chlorite	A	S	c	Pyrolusite	A	s	r
Chloritoid	D & ? A	s	r	Pyrrhotite	A	U	l
Chromite	D	s	vr	Quartz	D	S	c
Cordierite	D	U	r	Rutile	D & A	S	c
Corundum	D	S	r	Serpentine	D & A	s	r
Diopside	D	S	l	Siderite	A	s	l
Dolomite	A	S	l	Sillimanite	D	S	r
Dumortierite	D	S	vr	Sphalerite	D	S	vr
Enstatite	D	s	r	Spinel	D	S	r
Epidote	D & A	S	c	Spodumene	D	S	vr
Fluorite	D & A	S	r	Staurolite	D	S	c
Galena	D	S	l	Titanite	D & A	S	r
Garnet	D	S	c	Topaz	D	S	c
Glaucanite	D & A	s	c	Tourmaline	D	S	c
Glaucophane	D	s	r	Tremolite	D	s	vr
Graphite	D & A	S	r	Vesuvianite	D	S	vr
Gypsum	A	S	l	Xenotime	D	S	vr
Hæmatite	D & A	s	c	Zircon	D	S	c
Hornblende	D	s	c	Zoisite*	D	S	r

N.B.—In the above table the tendencies are denoted as follows:—occurrence (*Occ.*) by D=detrital, A=authigenic, and D & A=both; stability (*Stab.*) (chemical) by S=stable, s=moderately stable, and U=unstable; comparative frequency of occurrence (*Freq.*) by c=common, l=local, r=rare, and vr=very rare.

* Including Clinozoisite.

“ Under normal conditions the number of different mineral species occurring in sediments is not great; possibly twenty-five is a fair average for detrital deposits, especially of younger geological age. Older geological deposits (pre-Permian)

tend to have a much more restricted composition. . . . Allowing for certain environments where special types of igneous or metamorphic rocks constitute the source of supply of material, the list of possibilities is much larger, though the number of actually occurring species may be comparatively small. Under still more local conditions, for instance, where rarer types of metamorphic rocks or even metalliferous ores contribute material, it is obvious that any stable mineral may occur in the derived sediment if initially present in such parent rock-types."¹

The following notes are intended to be suggestive, not dogmatic:—

Actinolite. Fails to survive prolonged transport; presence usually suggests proximity of parent-rock (metamorphic); incipient alteration to serpentine indicates hydrous environment; to calcite, lime infiltration or influence.

Anatase. Generally authigenic: see under *Ilmenite*.

Andalusite. Degenerates with time; may be replaced by kaolinite in "sealed" environments; alteration to mica denotes hydration, and is facilitated by high porosity of sediment. When plentiful a possible indicator of geologically young deposits; universally wide-spread in Pliocene sediments, especially the most porous arenaceous developments; has been recorded from Old Red Sandstone (Mackie). An anti-stress mineral.

Anhydrite. Originates in the majority of cases by precipitation from saline solution, one of the earliest products to crystallize out with the process of gradual desiccation of land-locked waters. Commonly associated with rock-salt, gypsum and other sulphates. Is readily changed into gypsum by hydration, but the reverse reaction is also possible and has been observed. It may also form at the expense of limestone. In thick deposits or massive state is inferential of lacustrine, lagoonal or land-locked sea environment. In the presence of excess of organic matter, anhydrite may be reduced and deprived of its sulphur or,

¹ H. B. Milner, *Mining Mag.*, 1923, p. 80.

put in another way, access of methane to anhydrite (or gypsum) produces calcium carbonate, sulphuretted hydrogen and water; the reaction is probably reversible, and this accounts for the diversity of conditions under which anhydrite is found. This mineral should always be studied in its relationship to associated salts and other rock-types.

Apatite. Survives in argillaceous (impervious) rather than arenaceous (porous) rocks, or in "sealed" sediments, e.g., loamy Thanet Sand protected by cover of Chalky Boulder Clay (Boswell); destroyed in lime environments by solvent action of carbonic acid generated by percolating water; present usually in silt, clay, shale or red marl, products of continental, lacustrine, fluvial, rarely brackish marine environments. Degenerates under marine conditions forming secondary phosphates aided by organic selection (see *glauconite*). Has been noted in Old Red Sandstone (Boswell).

Aragonite. Given the presence of magnesium sulphate in solution and a temperature exceeding 29° C, any carbonate which may be precipitated will be aragonite, not calcite. In this way much of the aragonite is formed which occurs in association with limestone and saline deposits, though another source is the shells of certain organisms (p. 309). Aragonite indicates, *ceteris paribus*, climatic control and a warm sea. The presence of sodium or ammonium carbonate in sea-water favours its precipitation; under conditions in which organic decay is prevalent, the ammonium compounds would tend to be formed, especially in warm environments, thus aiding the deposition of aragonite. This mineral changes easily to calcite, but the reverse process has not been observed authoritatively.

Augite. If in quantity and fresh, indicates either proximity to parent-rock or preservation in anhydrous environment; degenerates with time, hence met with normally in youthful deposits. An anti-stress mineral. (See *Chlorite*).

Axinite. Beyond suggestive of pneumatolytic provenance, usually the product of contact-alteration of basic (lime-bearing) igneous rocks, this mineral is of no special significance.

Barite. Normally authigenic, but may be locally derived; cementing medium of porous, arenaceous rocks suggesting percolating carbonate- and sulphate-charged waters; or reaction between bicarbonate (infiltrating) solution and pyrite under oxidising conditions; initially liberated

(as barium oxide?) by decomposition of barium-bearing felspar and mica, especially by subaerial weathering of acid igneous rocks, and as an authigenic mineral tends to characterize continental (arid) or lacustrine deposits. In marine sediments (rare) may be segregated by organisms (*rhizopods*): see Samoilov, *Mineralogical Mag.*, xviii., 1917, p. 87.

Biotite. If in quantity and fresh, often implies occurrence in "sealed" deposit, especially lenticular sandstone in clay or shale; in porous deposit rapidly hydrated; this change may be suggested by presence of minute but perfect zircon crystals (thus released), providing contrast in type with the zircon characteristic of the deposit. Brown variety more stable than the green in sediments.

Brookite. See under *Ilmenite*.

Calcite. Seldom detrital in sediments of geological age; a highly stable product of the "lime environment"; derived from percolating lime-bearing solutions, or from organic sources; suggestive of aqueous rather than terrestrial environment, though may be formed under fluvial and lacustrine conditions. Too ubiquitous to be indicative of very precise environments.

Cassiterite. Locally significant of distributive province; durable except under hydrothermal conditions (impregnation of porous sediment by thermal waters). Has been recorded from Triassic deposits (Boswell).

Celestite. When in association with other saline deposits, *e.g.*, anhydrite, gypsum, rock-salt, also with limestone, the presence of this sulphate points to much the same environmental conditions as do those deposits. It can be formed directly from sea-water with or without the action of organisms. In association with freshwater marls, etc., it implies direct precipitation from those waters, the ultimate source of the strontium being igneous rocks. The presence of this mineral is to be anticipated in the above-mentioned rocks, but it appears to be sporadically developed and not in itself significant of any peculiar conditions beyond those noted.

Ceylonite. Of no special stratigraphical significance; may be anticipated where corundum, andalusite, sillimanite and kyanite are *all* present; under some conditions its absence may be due to alteration to steatite.

Chalcedony. Seldom detrital; more commonly the cryptocrystalline product of secondary silicification by infiltration of aqueous solution; of debatable nature and significance.

Chiastolite. Like andalusite, of which it is a variety, an anti-stress mineral, but probably less stable chemically and physically than that species; unlikely to survive re-deposition; under conditions of hydration, prone to alteration to mica, presumably with separation of carbonaceous matter; to be anticipated locally in semi-porous, fine-grained sediments.

Chlorite. Prevalent chloritic matter in sediments is suggestive of original occurrence of ferromagnesian minerals, *e.g.*, augite, hornblende, biotite, etc. It is doubtful whether any precise member of the chlorite family is identifiable as a detrital mineral, owing to possible variation in composition. Chloritisation has probably proceeded in most cases before the original species reaches the sediment; incipient alteration noted in detrital augite, hornblende, biotite, tourmaline (?) suggests, however, contemporary change. Chloritic products chiefly noted in "open," coarse sediments to which meteoric waters have easy access; they are far less common in "sealed" deposits.

Chloritoid. In so far as sediments are concerned, ottrelite seems to be far less stable than chloritoid, but primarily little seems to be known of the real composition and genesis of these minerals. Some of the Brittany chloritoid is suggestive of derivation *in situ*; in other cases it is clearly derived. As a local stress mineral, its occurrence in sediments is hardly suggestive of more than provenance.

Chromite. Tends to localize the source of the sediment in which it is found, but has little, if any other stratigraphical value.

Clinozoisite. See under *Zoisite*.

Cordierite. An unstable mineral, especially in sediments; in a hydrous, alkaline environment it changes to micaceous pseudomorphs such as pinite; it may be produced in sandstone by "vitrification" due to contact with igneous rock-magma (Bücking, quoted by Clarke, *Data of Geochemistry*, 1924, p. 410). It tends to be preserved in impervious deposits not far removed from source of origin. Has been recorded from Carboniferous and Triassic deposits (Boswell).

Corundum. Although primarily a stable species, prolonged action of percolating water may produce alteration products, *e.g.*, diaspore; dissolved salts in such waters may, by coincident action, produce various compounds, *e.g.*, muscovite, chloritoid, zoisite, etc. It is suspected that such

changes are capable of taking place in porous sedimentary environments, but to what extent is unknown; this may account for the increasing rarity of corundum in deposits of geological age. It tends to be commoner in marine than in other types of sediment: a saline environment may retard alteration, hence its preservation, but further observations on detrital occurrences are required.

Diopside. In sediments is prone to alteration to serpentine, calcite, etc., though in "sealed" deposits fresh grains may be preserved; probably would not survive prolonged transport or re-deposition.

Dolomite. In detrital sediments almost invariably authigenic, and characteristic of, but not confined to shallow water marine deposits; where dolomite is common and calcite rare, organic origin in a "magnesian sea" may be suggested; alternatively precipitation from percolating waters in continental deposits is possible, *e.g.*, where a magnesian limestone is laid under contribution; in this connexion it is noted that Palæozoic limestones tend to be more highly magnesian than those of younger geological age; thus an abundance of dolomite in a detrital sediment may presuppose the existence of Palæozoic limestone as a source of the magnesian carbonate. Absence of the lime carbonate would seem to indicate subsequent leaching action, facilitated by access of meteoric water through porous deposit; close textured or impervious rock, *e.g.*, marl, silt, favours presence of both calcite and dolomite, and this is frequently observed. Dolomitic limestone overlying porous detrital deposits may similarly contribute to the formation of the mineral in those sediments.

Dumortierite. Frequently significant of pegmatitic parent-rocks; also to be expected in association with kyanite, sillimanite, andalusite, etc.

Enstatite. Not a mineral to survive much mechanical or chemical stress; by hydration it alters to talc and serpentine, the former and much of the latter tending to be lost in the process of sedimentation.

Epidote. Both detrital and the product of a destabilising environment; in the latter case derived from ferromagnesian minerals, sometimes garnet, and invariably associated with chloritic matter; detrital epidote is frequently unaccompanied by chloritic minerals; the authigenic variety is consistent with continental and lacustrine deposition, detrital epidote being more frequent in marine deposits. Has been recorded from Longmyndian (Pre-Cambrian) deposits (Boswell).

Fluorite. Undergoes alteration in a sedimentary environment invaded by percolating water charged with bicarbonate or alkaline carbonate; sometimes authigenic, cementing sandstone (Mackie), or may be formed by replacement of lime carbonate by percolating fluoride solutions in porous sediments; may be significant of fluvatile or terrestrial deposits, but this is not invariable.

Galena. May impregnate porous sandstones, *e.g.*, Keuper Waterstones, Cheshire, otherwise mainly of alluvial derivation in proximity to sulphide deposits.

Garnet. Frequently by its form an indication of the intensity of æolian corrasion, aqueous abrasion, etc. Under certain conditions (? mechanical) it is singularly unstable and is "lost" in deposits where it might be anticipated to occur in quantity; chemical alteration in sediments is mostly to chloritic matter: some of the isotropic green grains observed in porous sands probably represent this change; non-survival may be due to chloritization following mechanical disintegration, but further observations are necessary.

Glaucinite. Where organic structure is evident, marine origin of its environment is seldom in doubt; derived glauconite, however, does occur, usually partially limonitised and lacking organic character (*e.g.*, Wealden deposits); frequently significant of stratigraphical breaks, *e.g.*, glauconite and phosphate development coincident with subaqueous unconformity between *dictyonema* shale and glauconite shale, Lower Ordovician, Scandinavia (Fearn-sides, *Geol. Mag.*, 1907, pp. 257-267, 295-304); also similar association at junction between Chattanooga shale and overlying Carboniferous, Tennessee, U.S.A. (Hayes, *U.S.G.S.*, 16th *Ann. Rep.*, 1895, pp. 611-612; 17th *Ann. Rep.*, 1896, p. 523); "... the more significant breaks in a stratigraphic series are likely to be marked by the occurrence of autochthonous glauconite, in many instances associated with, directly above the break or rarely more than a foot or two above it" (Goldman, *U.S.G.S.*, *Prof. Pap.*, 129, 1921, pp. 1-22; also "Association of Glauconite with Unconformities," *Bull. Geol. Soc., Amer.*, xxxii., 1921, p. 25; also *Science*, lvi., 1922, pp. 171-173). Where glauconite and phosphate occur, the latter predominates in littoral facies, glauconite in off-shore shallow water facies, *i.e.*, continental shelf (Anderson, *Bull. Inst. Univ., Upsala*, 2, 1895, pp. 133-236). Colour may be significant, depth of colour varying inversely with geological age: darkest green in Cre-

taceous and Tertiary beds, lighter green in Palæozoic, *e.g.*, Cambrian; survival of "ancient" glauconite mostly due to presence of impervious cover-rock. Both fresh and limonitised glauconite may be present in arable soil, owing its formation to adsorption of potassium compounds in this environment, the adsorptive media being soluble (colloidal) silica and colloidal ferric hydroxide. (L. Cayeux, *Ann. Soc. Géol. du Nord*, xxxiv., 1905, p. 146). The possibility of some soil-glauconite being derived by circulating waters is to be noted. Gravity may be significant:—higher gravity may indicate slightly limonitised glauconite of inorganic origin, therefore not necessarily in marine deposits; lighter gravity is more typical of "foraminiferal" glauconite, not so prone to alteration (gravity range 2.25 to 2.92). A species of great stratigraphical value in all circumstances (cf. A. F. Hallimond, paper cited, p. 183).

Glaucophane. A stress mineral of sporadic occurrence in sediments; may possibly be authigenic (decomposition product), especially if fresh (Koto, *Journ. Coll. Sci., Tokyo*, i., 1887, pp. 85-98). When detrital, often shows chloritic alteration; degenerates with geological age, being observed mostly in middle Tertiary to Recent deposits, especially Miocene marls and silts of widely separated countries.

Graphite. Much of the so-called graphite in sediments (usually recent or alluvial) is probably amorphous carbon derived by mechanical disintegration from minerals containing carbon inclusions, or else from hydrocarbon impregnation; otherwise of little geological significance.

Gypsum. Varied genesis; a favourable environment is that under which pyrite by oxidation can react with calcareous rocks; it may be fundamentally of marine origin, *i.e.*, concentration of saline waters by desiccation; deposition from infiltrating freshwater solutions containing lime-salts will determine its appearance in many porous deposits; often of considerable stratigraphical significance. (See also under *Anhydrite*).

Hæmatite. Tends to be common only where sediment is "sealed," or where infiltration of meteoric water is prevented by impervious cover, otherwise rapidly hydrated to limonite.

Hornblende. Sometimes a difficult mineral to interpret; is freshest in "sealed" deposits, much chloritised in porous sediments; the brown variety seems to be much less stable, and may be a criterion of geologically recent formations; green hornblende has a much greater time-range,

and would seem to be favoured by marine environments, e.g., Ordovician, Upper Lias-Inferior Oolite, Portland Sand, Aptian, Eocene, Miocene, Pliocene, etc.

Hypersthene. As for *Enstatite* (q.v.).

Ilmenite. "The titanium minerals are . . . closely connected with one another, and transformations are possible in almost every direction" (Clarke, *Data of Geochemistry*, 1924, p. 355). This concerns ilmenite, anatase, rutile, brookite, titanite or sphene, leucoxene, possibly perovskite (unrecorded as detrital), and locally pseudo-brookite (a rare accessory of volcanic rocks, also unrecorded in sediments). Majority of anatase grains are authigenic, i.e., generated *in situ* at the expense of ilmenite or other titanium species; brookite is sometimes authigenic, though it alters to rutile in suitable environments; its comparative scarcity may be due to this fact, much of the large, ill-shaped, dirty-brown rutile possibly representing this reaction; rutile is both derived and authigenic, similarly titanite and leucoxene; the geochemical mechanism of these transformations may be reasonably clear, but the selective operation of any particular tendency in a sedimentary environment is not so obvious and requires investigation. The ilmenite-leucoxene ratio alters in favour of the latter with increasing geological age of the enclosing sediment, but seems to bear little relationship to the occurrence of the oxides or titanite; a reciprocal relationship has, however, been noticed between titanite on the one hand, and anatase and brookite in the same deposit on the other (Boswell, *Geol. Mag.*, 1924, p. 267). "Biotite altering beneath a capping of turf and in a sour water environment is likely to undergo complete disintegration, and it appears at least possible that (a) its decomposition products include a more or less colloidal complex of titania and silica, and that (b) the silica and titania may slowly disengage themselves and become crystalline: the silica may expend its potential energy in repairing and extending quartz grains, or in initiating new ones; in a similar way, titania may apply itself to anatase. It is also possible that the alteration of ilmenite to granular anatase proceeds via a complex of hydrated ferric oxide and hydrated titania, and anatase nuclei thus authigenically produced could receive extensions in the manner suggested above" (A. Brammall and H. F. Harwood, *Mineralogical Mag.*, vol. xx., 1923, p. 24). The instability of allothigenic biotite under certain

sedimentary conditions is capable of initiating a similar mechanism, and enquiry into the provenances of British sediments rich in transparent titanium minerals in most cases points to the presence of sufficient black mica for the purpose in the parent-rocks concerned. The development of anatase is facilitated by high porosity and ill-graded sediment, implying facility of "sour water" circulation. The generation of leucoxene and titanite (according to Cathrein synonymous terms—see *Zeitschr. Kryst. Min.*, vol. 6, 1882, p. 244) suggests a similar environment, and it is observed that leucoxenic alteration is at a maximum in coarse sediments; authigenic titanite may be initiated with the formation of titanium-bearing chloritic minerals from decomposed amphibole-rich parent-rocks, since chlorite is often observed in concentrates in which titanite is conspicuous; the presence of lime is, of course, essential. Where lime is absent or at a minimum, especially in an iron-rich environment, the ilmenite—rutile—anatase—brookite tendency (in order of decreasing frequency) seems to predominate; in a neutral environment the leucoxene—titanite—perovskite tendency may be strong, but there is difficulty of achievement, certainly of persistence, in the case of the two latter species, attested by their scarcity in detrital deposits; alternatively, they may be formed initially in a sedimentary environment, but owing to chemical instability or unfavourable "atmosphere," the titanite—rutile—ilmenite tendency may be promoted. Careful observation of the occurrence and association of the titanium minerals in all kinds of sediments is needed before their individual or collective significance can be fully appreciated.

Kaolinite. Known chiefly as an alteration product of feldspathic minerals, sometimes by pneumatolysis, but in sediments by the action of humous acid (if near the surface) or of percolating water and carbonic acid. Frequently accompanied by sericitic mica. Rare as an individualized mineral in sediments; usually noted as a decomposition product in deposits which are ill-graded or "open"; is not confined to, and is often totally absent from, argillaceous rocks. (See Schwarz and Walcker, *Zeit. f. anorg. chem.*, cxlv., 1925, pp. 304-310).

Kyanite. A stress mineral. Chemically stable and resistant to acidulated percolating waters in sediments, to which its remarkable persistence may be ascribed. Susceptible of disintegration under mechanical stress, and may

thus be an indicator of the intensity of the forces implied, largely due to its prevalent cleavages.

Lepidolite. In detrital deposits may be secondary after muscovite (q.v.).

Leucoxene. See under *Ilmenite*.

Limonite. Commonly implies the oxidation and hydration of iron-ores such as pyrite, pyrrhotite, marcasite, and is also formed from magnetite, hæmatite, ilmenite and other iron-bearing minerals. Oxidation of sulphidic iron-ores produces firstly soluble sulphate, afterwards precipitated as hydroxide; process aided by carbonic acid in percolating water; organic acids also potent in this respect. In detrital sediments limonitisation proceeds where the rocks are porous and where iron-bearing solutions have ready access to them; or in a "sealed" environment alteration of original iron sulphides or oxides may take place slowly. Limonite in detrital sediments is frequently prolific in proximity to glauconite-bearing rocks, implying the formation by alteration of the glauconite. Limonite is so ubiquitous in sediments and its genesis is so varied, that in the absence of other evidence it is seldom of any special significance.

Magnetite. Pure magnetite is far less common in detrital sediments than is generally thought; usually it is detrital, but it may also result from alteration of marcasite and pyrite (Van Hise) or from the oxidation of siderite. It is most characteristic of fine-grained, semi-porous deposits where infiltrating solutions are less potent.

Marcasite. The unstable isomer of pyrite and nearly always authigenic. Best preserved in a neutral environment or in the presence of lime; its organic origin is frequently suggested by its occurrence in association with fossil shells almost invariably in marine deposits; an hermetically "sealed" environment aids its preservation.

Microcline. A valuable indicator of climatic conditions attending deposition of the sediment in which it occurs (p. 432).

Monazite. The alteration of this mineral to an aggregate in which cerium oxide is conspicuous tends to be superficial, but in deposits of geological age seems to proceed under conditions implying humid, estuarine environment; fresh, unaltered monazite, though characteristically "worn," is of little significance other than of provenance.

Muscovite. When detrital, its disproportionate size relative to associated constituents is noteworthy and signi-

ficant of its buoyancy, especially in an aqueous medium. May be authigenic, formed from feldspar, topaz, andalusite; or may represent certain feldspathoid minerals. Some muscovite observed in sediments represents bleached biotite (c.f. optical properties), implying action of acidulated solutions whereby iron oxide and alkalis are removed, and hydration promoted. *Sericite* is invariably secondary, and is a stress mineral; white mica is more prolific in fluvial and estuarine arenaceous sediments than in similar deposits of marine origin, or conversely in marine, rather than in fluvial or estuarine clays.

Olivine. Fresh, unaltered detrital olivine is rarely, if ever, found in sediments of geological age, decomposition to serpentine, talc, epidote, etc., being easily achieved, especially in a hydrous environment. It is thus characteristic only of Recent deposits (shore sands and alluvials, not far removed from source of origin. Essentially an anti-stress mineral.

Orthoclase. A valuable indicator of climatic conditions attending deposition of the sediment in which it occurs. Does not long survive a hydrous environment, especially if percolating waters are acid, or if any associated sulphide ores are undergoing oxidation whereby acid may be liberated *in situ*. Meteoric water containing carbon dioxide also attacks it. Such alteration is usually indicated by the presence of kaolinite, mica, or hydrous silicates of alumina; mica will not be formed if alkalis have been removed. In the presence of lime and iron, epidote or zoisite may form. An anti-stress mineral.

Picotite. Of no apparent significance save as an indicator of parent-rocks.

Plagioclase. In sediments the soda-bearing feldspars are more stable than the lime-bearing species. *Labradorite*, *bytownite* and *anorthite* are prone to decomposition by percolating waters charged with carbonates whereby calcite and free silica are formed. Partial decomposition of *anorthite* under similar conditions results in the production of epidote, zoisite or actinolite. Sericitization by meteoric waters containing carbon dioxide is possible. Albite may be classed as a stress mineral, but *anorthite* is essentially an anti-stress mineral. The comparative scarcity of plagioclase in detrital sediments is clearly due to one or more of the possible processes of alteration, and the presence of well-formed (unabraded) authigenic minerals as suggested, may quite well indicate the type of change accomplished,

and thus throw light on the environment in which it has been achieved.

Pyrite. Is most characteristic of impervious clays, shales and muds where it is usually authigenic and suggestive of organic origin. In a reducing environment, especially under marine conditions, sulphates are converted to sulphides by the decomposition of organic matter; in the presence of CO_2 sulphuretted hydrogen is formed which, by reaction with iron silicates, forms pyrite, marcasite, etc. Alternatively, bacterial influence may account for the H_2S . The frequent occurrence of pyritised casts of micro-organisms is suggestive of the mechanism above outlined. The occurrence of pyrite bears an interesting relationship to the colour of the sediment containing it, whereby considerable light may be thrown on the environment of sedimentation: it is rare in red rocks, usually inferential of oxidising conditions and frequently the colour of terrestrial (fluvial and æolian) deposits; it is sporadic in blue or bluish-grey rocks, especially clays, usually suggestive of reducing reactions in excess of oxidising influences; it is most common in black or blackish-grey clays or muds formed in a reducing environment, often implying biochemically toxic conditions; in green rocks it tends to be rare or absent where the colour is due to chloritic products (resulting from decomposition of ferromagnesian minerals), in which case the chloritic matter is apparent; more common where the colour is due to glauconite. These circumstances are exemplified by the Stockdale Shales (Silurian) of the Lake District (Marr, *Q.J.G.S.*, lxxxi., 1925, p. 113 *et seq.*), where benthonic organisms are absent in the black muds (pyrite and carbon common), rare in the green and some of the red muds, fairly abundant in the blue and part of the red muds: absence, rarity or observed dwarfing of these organisms is ascribed to toxic influences, sulphuretted hydrogen or iron hydrate. Thus pyrite, apart from its own significance, should be interpreted in conjunction with organic evidence if available; this mineral, together with its oxidation products, will frequently throw a flood of light on the nature of the environment from both biological and geological points of view.

Pyrolusite. A product of infiltration, usually observed on joint planes of calcareous rocks. In some cases it may be traced to swamp deposits associated with limonite, from which it is transported into underlying rocks by descending meteoric waters, but often its origin in sediments is obscure.

Pyrrhotite. The origin of this mineral in detrital sediments is not always clear, but it tends to occur only in "sealed" sediments beyond the reach of oxidising or acidulated waters of meteoric origin, though it is itself almost invariably authigenic; probably formed as a result of biochemical processes.

Quartz. This essential mineral of detrital deposits is significant of environment chiefly by reference to its form (nature and degree of abrasion), while a study of its inclusions is often of prime importance in tracing the source of the deposit concerned.

Rutile. See also under *Ilmenite*. Rutile is a possible stress mineral. Perfect euhedral forms in detrital sediments are probably authigenic, but derived rutile, often much fractured, is met with particularly in æolian deposits.

Serpentine. Nearly always authigenic and formed by the action of percolating waters charged with magnesia on non-magnesian minerals; or may be generated *in situ* by the decomposition of olivine. Does not survive transport for great distance, and is frequently indicative of proximate parent source of the sediment concerned.

Siderite. Frequently significant of a fluvial or lacustrine environment, especially in fine silts and clays in which vegetable organic matter is present. Infiltrating waters charged with carbonic acid may, in the presence of organic matter, result in the formation of siderite, though in porous rocks calcite and limonite are the more likely products. Spencer suggests another mechanism (*Q.J.G.S.*, lxxxi., 1925, p. 687), "that the iron compounds present in solution as soluble carbonates, humates, or hydrolyzed and possibly colloidal hydrates, were absorbed by the fine-grained and partly colloidal sediments, and carried down with them during deposition." Clay-ironstone is a precipitate deposit tending to form about organic nuclei under terrestrial (as opposed to marine) conditions. Oolitic forms of siderite are frequently accompanied by the mineral chamosite, an iron silicate, as in the Cleveland deposits (*Sum. Prog. Geol. Surv. Gt. Brit.*, 1922; see also A. F. Hallimond, *Mem. Geol. Surv., Spec. Rep. Min. Res. Gt. Brit.*, xxix., 1925) and imply weak carbonation; strong carbonation is productive of clay-ironstone; spherulitic siderite can only be produced in the absence of chamosite (Spencer). Thus a detailed study of siderite in sediments may be highly suggestive of their mode of formation and environment.

Sillimanite. A highly stable species, but of little significance save as an indicator of provenance.

Sphalerite. (*Zinc Blende*). Tends to localize the deposit in which it is found.

Sphene (*Titanite*). See under *Ilmenite*.

Spinel. See under *Ceylonite* and *Picotite*.

Spodumene. The lithia-bearing pyroxene, chiefly significant of its association with coarse pegmatites to which source its origin in sediments may often be traced. Very susceptible to alkaline solutions by which it is changed into albite, muscovite, etc. An anti-stress mineral.

Staurolite. A stress mineral. Is frequently suggestive of provenance, but is independent of facies, and not inferential of any particular sedimentary environment. Pre-Armorican record from Llandovery (Silurian) of the Midlands (Boswell).

Titanite; see under *Ilmenite*.

Topaz. Frequently occurs under the same conditions as andalusite, but is more stable than that mineral, and has a wide stratigraphical range; noted in Upper Silurian deposits. In an alkaline environment (infiltrating alkali-bearing solutions) a change to muscovite (damourite or sericite type) is possible.

Tourmaline. An ubiquitous detrital species on account of its stability, though under certain conditions is liable to micaceous and chloritic alteration. May survive more than one erosional cycle, when its worn character, together with other criteria may be significant.

Tremolite. A stress mineral, sometimes replacing pyroxene; is not so stable as ordinary hornblende, and does not survive prolonged transport or re-deposition; hence it tends to localise the deposit in which it occurs.

Vesuvianite (*Idocrase*). Significant of provenance.

Xenotime. A problematical species in detrital sediments on account of the difficulty in its certain diagnosis; may be anticipated where monazite is prevalent, but has little other significance.

Zircon. An almost invariable accessory mineral in detrital deposits, and, like tourmaline, may survive several erosional cycles; colour and inclusions are significant of provenance. See also under *Biotite*.

Zoisite. A stress mineral to be anticipated in association with hornblende, glaucophane, epidote, etc., and probably more common in sediments than usually supposed, a remark equally applicable to clinozoisite.

CHAPTER XI.

THE APPLICATION OF SEDIMENTARY PETROLOGY TO THE STUDY OF SOILS AND RELATED SUPERFICIAL DEPOSITS.

Introduction — Modern Conceptions of Soil Constitution—
Classification of Soils—Soil Colouring—Mineral Com-
position of Soils—Mechanical Analysis of Soil Particles—
—The Function of Petrology in Soil Studies—Selected
Bibliography.

The investigation of soils and related superficial deposits from the petrological standpoint, along the lines laid down in this volume for sedimentary rocks in general, is a comparatively new departure. This application has in recent years attracted attention in many soil and agricultural research stations both at home and abroad, though its potentialities seem as yet to be imperfectly understood.

Efforts have from time to time been made to awaken geological interest in superficial deposits, especially soils, for their own sake, seemingly without much success. It must be admitted that advancement of knowledge of soils, more particularly as regards nature and constitution, has evolved largely from the labours of the agricultural chemist and physicist. In the process of drift surveys, superficial deposits as such have naturally received due recognition and study, but the uppermost soil-layers have only too frequently suffered neglect. Certainly the resources of the

modern geological laboratory have seldom been invoked to determine the soil as a rock, save in instances hereafter cited.

The geologist is inclined to regard soil as the inevitable blanket concealing his rocks and limiting his outcrops. His interest in it begins and ends with its larger rock-components turned up by the plough on cultivated land or exposed by some other means. Even prehistory, that happy common ground of geologist and anthropologist, denies to the soil more than recognition as a possible medium in which lie scattered human relics.

G. W. Robinson,¹ in a suggestive article "Pedology as a branch of Geology," has drawn attention to this state of things. He writes as follows:—"We have in our own country scarcely any research in which the material (soil) is treated from a purely scientific point of view and studied in the same way as rocks have been studied by geologists." R. H. Rastall,² in his book "Agricultural Geology," discussing soil characteristics, says, "The agricultural value of a soil depends on a large number of factors, only some of which are within the province of the geologist. Pre-eminent among these are its mineralogical composition and the state of division of its particles; on the former subject little work has been done, and a large field of research is here open, especially with regard to the mineral character of the smaller particles."

It has frequently been the author's lot in the course of his work on sediments to investigate superficial deposits, including various types of soil, in equal petrological detail with those of

¹ *Geol. Mag.*, lxi., 1924, p. 444.

² *Camb. Univ. Press*, 1916, p. 143.

geological age. Experience has shown conclusively the value attaching to this study, both from scientific and economic motives. It is the present contention that all deposits, of whatever character, lying above the solid-rock zone, are worthy of the same careful petrological attention as is accorded the more familiar strata, and it is the purpose of this chapter to establish the truth of this dictum.

Soils present a variety of difficult problems which go to make common research territory for the biochemist, physicist and geologist. Modern conceptions of their nature, constitution, mineralogical composition, mechanical analysis, relationship to bedrock, and significance as products of contemporary or relatively recent formation, are all matters of geological concern. The application of petrographic methods is an obvious step towards the better understanding of these features, possibly towards a solution of some of the more obscure problems of soil-genetics. There is none better qualified than the sedimentary petrologist to undertake the study and contribute the data required. In fact, a liaison between the pedologist and petrologist may be said to have been long since established when we recall the extent to which mechanical analysis of sediments has been influenced by the relevant work of soil-analysts in the past.

The term soil is subject to varied definition. Technically it is the most superficial portion of the "regolith,"¹ that useful word of Merrill's to cover the "entire mantle of unconsolidated material, whatever its nature or origin," as distinct from solid rock. In its narrower and popular sense, soil is essentially the medium supporting plant-life.

¹ *Rocks, Rock-Weathering and Soils*, 1913, p. 287.

The agriculturalist's interpretation is roughly that of the cultivated zone extending downwards to the limit of implement penetration. Considered from the point of view of pasture-land, the soil carries and supports the growth of the roots.

Beneath the soil and by gradual transition lies the subsoil zone, usually an indefinite deposit of composite character. It affords a complete passage between the soil and bedrock, the lower-most layers showing obvious affinities with the latter, chiefly by the detached rock-fragments

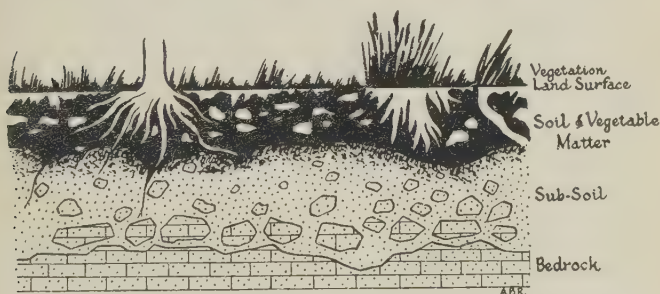


FIG. 181. Soil-Relation to Bedrock.

forming the "float," the higher layers having more sparsely scattered rock-fragments, lesser compaction, and a marked resemblance to the soil itself (fig. 181).

In drift-covered areas the soil rests on some particular type of sedentary or transported material forming part of the regolith. Actual bedrock in this case may be buried under considerable thickness of superficial deposit. Where the latter is the product of transport, *e.g.*, alluvium, the soil shows affinities with it and not with bedrock. Where sedentary deposits are concerned, *e.g.*,

residual clay, laterite, etc., some connexion is usually traceable throughout the bedrock—soil sequence. Petrological investigations serve to differentiate between such conditions and to confirm field-observations.

MODERN CONCEPTIONS OF SOIL CONSTITUTION. The trend of chemical and physical research on soils has been to demonstrate conclusively that soil, as a form of matter, is fundamentally a colloidal system. Thus a distinction is automatically drawn between soils and most sedimentary rocks (except certain clays and finely divided incoherent deposits) whose constituents are essentially crystalline. To a large extent the nature of soils, their physical properties and behaviour under different climatic conditions, are all governed by the presence of this colloidal complex which, broadly speaking, is composed of colloidal organic matter and colloidal clay. In addition, there is a varying amount of mineral- and rock-particles entombed in this complex medium.

In the case of a so-called clay soil, colloidal matter is in excess of mineral matter, itself in an extremely fine state of division. In a more "open" or sandy soil, the mineral matter is composed of larger particles and may predominate over the colloidal elements. In certain cases the colloidal complex is reduced to a minimum, though it is seldom that the organic colloids are completely absent.

Thus variations in soil characteristics are fundamentally determined by slight variations in either the colloidal system or in the mineral aggregate, or both.

In so far as petrology may concern itself with soil constitution, it is clear that determination of the colloidal organic components, for the most part

of vegetable origin, lies completely outside its scope. Colloidal clay, on the other hand, furnishes much the same problem as does the clay-substance of argillaceous rocks; both represent the end-products of destabilisation of the common rock-forming silicates, and there is no vast difference between their investigation either in the soil environment or in the more familiar plastic clay; petrology is concerned equally with both, though it is only recently that it has been able to throw a little light on the real nature and origin of those difficult materials (p. 284).

It has already been explained (p. 264) that the old conception of clay as a manifestation of the mineral "kaolinite" is obsolete. So with soils. The pedologist no longer regards his colloidal clay complex merely as a state of kaolinite. "Colloidal clay would appear to be of the nature of an 'adsorption compound' of indefinite composition containing silicic acid, and the hydrated oxides of iron and aluminium. Iron oxide is almost invariably associated with aluminium oxide and appears to fulfil a similar role in the clay complex."¹

With the mineral- and rock-particles constituting the "float," petrology is obviously concerned in many ways. Apart from their determination as soil ingredients, their study infers the extent to which contiguous or underlying geology has influenced the soil constitution. As with other sediments, these mineral components afford a basis of comparison of different soils in a particular region, or of their differentiation. Their study is a potential guide to distinction between sedentary and transported soils, equally to contamination of one type by another.

¹ G. W. Robinson, *op. cit.*, p. 445.

In another direction, mineral- and rock-particles in soils are susceptible of mechanical analysis, not merely as a means of classifying the soils involved (as sought by some physicists), but as a measure of porosity, permeability, movement of particles within the soil medium, and movement of the soil itself; to a lesser extent as an indication of direction of movement.

Both mineralogical and mechanical constitution of soils are dealt with more fully in the sequel.

CLASSIFICATION OF SOILS. It is not within the province of this book to discuss the various systems of classification proposed for soils. Some reference must, however, be made to such aspects of the matter having direct bearing on petrological investigations, or which may well be influenced by such research.

Actually there is much difference of opinion among soil technologists as to the most philosophical scheme applicable to all soils. Practically every classification designed so far has been subjected to severe criticism from one quarter or another. The problem reflects that with which petrologists are confronted for normal rocks, or perhaps "abnormal" would be the better word, since it is essentially the abnormal types which prove obstructive to most schemes invented. Abnormalities in soils are even more pronounced than in other sedimentary deposits; added to this there is the uncertain colloidal element in soils which makes them extremely difficult to fix with precision into any specified category.

At the outset a geological classification would seem practicable where this implied soil characters dependent on bedrock characters, and petrological work would tend to support such classification. There is, however, wide divergence between soil

and bedrock in many cases, clearly in instances where soils have undergone transport. Studies in plant ecology illustrate this point forcibly.

The dry, somewhat sterile soil of the wide sandstone tracts tends to favour conifers, gorse, bracken, etc. Shale and clay determine the formation of colloidal soils on the whole characterized by deciduous vegetation, *e.g.*, oak, poplar, etc. These observations are subject to many qualifications of place, climate and the like; normally, however, they hold good and exemplify the soil-geology relationship. On the other hand, calcareous rocks not infrequently support soils which, in constitution, are the antithesis of calcareous; sometimes by virtue of superficial contamination they may even be sandy and support a dominantly coniferous vegetation. The latter illustrates discordance between soil and geology and shows where a classification, based entirely on bedrock character, would at once break down.

Comber¹ in his recent little book writes, " But even in areas where the geological distribution of soils is of practical use, the relation of soil properties to geology is by no means perfect. This partly arises from the fact that two areas may be geologically the same and yet differ very much lithologically. It also arises from the fact that the same rock under different weather conditions will give rise to a different soil."

As previously indicated, it is possible by petrographic means, taking into consideration the complete sequence of regolithic deposits, to differentiate between sedentary or residual and transported soils, and the distinction is undoubtedly a useful one. Alternatively, if mineral

¹ N. M. Comber, *An Introduction to the Scientific Study of the Soil*, London, 1927.

components can ever be made criteria of certain definite types of soil, petrology may be anticipated to provide relevant data; but beyond this it would seem that geology as a whole has little to offer towards a comprehensive soil classification.

The purely physical classification recognizes organic or humus soils, calcareous soils, and mineral soils. The latter comprise the sands, loams and clays (as soils), mechanical constitution of the mineral group being the arbiter of distinction. It may be pointed out, however, that, unlike normal sediments, mechanical analysis cannot in itself afford an indication of particular soil types, again for the reason that the organic matter, also what the pedologists know as the "lime status" of the soil, varies widely and must be taken into consideration.

Possibly the most generally acceptable primary division of soils is due to Glinka;¹ this takes the state of the soil into consideration, only indirectly implying geological process and influence. Glinka propounded two main groups, the immature or endodynamomorphic soils, and the mature or ektodynamomorphic soils. In the former, destabilisation of the rock-forming minerals involved is incomplete; there may or may not be some relationship still discernible between soil, subsoil and bedrock; the question is susceptible of treatment from a petrological standpoint.

In the case of the mature soils, whatever influence parent-rocks may have had initially, has been obliterated by subsequent changes in the soil system; the material thus becomes the object of entirely independent investigation. The mature

¹ K. Glinka, *Die Typen der Bodenbildung, ihre Klassifikation und geographische Verbreitung*, Berlin, 1914. (See also ref. on p. 472).

soils, which are still further subdivided, are also capable of petrological analysis up to a point, especially on the basis of their stable accessory minerals, inherently persistent into any peculiar soil environment. Each example must of necessity be dealt with on its own merits.

SOIL COLOURING. The natural colouring of certain soils invites observation as affording some indication of the character of the underlying rocks, though the explanation of particular colours is by no means always straightforward. Colour in soils may imply the influence of either organic or inorganic agencies, or both; it may be a secondary, even transient development in response to some biochemical process in operation in the soil environment. This is particularly the case in the uppermost soil layers where vegetation becomes the potent factor: witness the well-known leaching action of peat humus on iron compounds in sandy soil.

Soil colouring, as is the case with clays or, for that matter, with all sediments, is significant and should be investigated. The enquiry is partly chemical, partly petrological; the deductions are matters of common scientific and economic interest. Where prevalence of individual minerals is responsible for the colour of a soil, *e.g.*, hæmatite, limonite, glauconite or chlorite, the analysis is a simple one. Where, however, the colouring matter is varied, diffused or attributable on petrological examination of the soil to no particular mineral, it is impossible to settle its identity without recourse to exhaustive chemical testing, just as is necessary with clays, for instance.

The analogy between stratigraphical clay colouring and that of soils is close. Black, dark grey and grey are normally characteristic of soils whose

colloidal content is high, due to the products of anærobic decay of vegetable matter, often under swampy conditions. In dense black soils the carbonaceous element is usually present in excess.

Yellow, buff or ochreous soils owe their colour chiefly to hydrated oxide of iron, *i.e.*, finely divided limonite. Red soil is determined by prevalent red oxide of iron. Pale coloured soils, varying from white to dirty yellow, may be inferential of either calcareous components or sometimes of soils rich in aluminous silicates or phosphates; light-coloured soil is, however, sometimes entirely devoid of lime. In contrast are the brown, even dark grey soils of certain limestone regions which are predominantly calcareous.

The existence of vivid colouring, *e.g.*, mauve, green, or variegated streaks, is sometimes noted; chemical analysis usually shows this to be due to the presence of some highly coloured chemical salt, presumably in colloidal suspension.

A section exposing the complete sequence from bedrock to surface soil layers, whether relationship exists between the two or not, if just opened and examined in the fresh state, serves to reveal the passage of primary to secondary colouring matter through the successive zones. Such observations invariably prove instructive, especially when coupled with the results of petrological examination of the materials involved. Apart from mineral decomposition and the consequent generation of destabilisation products, the action of meteoric water in its passage through the pervious layers determines certain changes in soil constitution accompanied with corresponding changes in colouring matter, while the organic reactions set up by various plants similarly find their colour expression. There is scope for profitable research in this direction.

MINERAL COMPOSITION OF SOILS. In so far as this can be stated in terms of definite minerals, the inorganic constituents of soils are fundamentally the rock-forming species, their decomposition products and the stable accessory, chiefly "heavy" minerals, familiar in detrital sediments. It has already been noted that the colloidal clay-content of soils owes its origin to the rock-forming silicates; this implies alkali and alkaline-earth compounds, or, expressed as minerals, mainly the feldspars, micas, amphiboles, pyroxenes, olivine, calcite, etc.

The accessory minerals may be represented by a large number of different species, as elsewhere described in this book. Normally it is the fundamentally stable minerals which are found, *e.g.*, ilmenite, tourmaline, zircon, garnet, rutile, anatase, titanite, etc., though in some soils the yield of ordinarily uncommon minerals, *e.g.*, olivine, augite, apatite, glaucophane, etc., is very striking.

It is often impossible to anticipate with certainty either the character or the richness of the heavy mineral yield from a soil, even where the bedrock constituents are known. This is one of the reasons why petrographical investigation of soils proves such a fascinating study, since the presence of one or more minerals, not found in the underlying rocks, or only occurring in rocks outcropping some distance away, immediately opens up interesting questions of provenance, incidentally of the natural history of the soils concerned.

The recognition of primary rock-forming minerals in soils depends largely on the degree of immaturity still retained. Obviously where such original species as feldspar, hornblende (especially in cleavage fragments), mica, olivine, etc., re-

leased from parent-rocks are still identifiable *per se* in the soil, and, moreover, can be matched close at hand in bedrock sections or concentrates, then the relationship between parent-rock and soil is at once unequivocally established. Actually such petrological relationship is likely to be more apparent in the sub-soil zone than in the uppermost soil-layers, where radical changes may have been accomplished.

Mineral composition of the soil naturally tends to vary with that of the rocks immediately underlying it, except in those cases where the soil itself has not been formed *in situ*. Two contrasted influences are at work; either the soil rests on solid rock (with intervening sub-soil) or on drift. In the first case the nature of the rock exerts a definite influence, particularly in the accessory mineral composition of the soil. In the case of a drift soil, that influence is an entirely unknown quantity.

Igneous rocks, plutonic, hypabyssal and volcanic, each contribute their peculiar stable accessories in addition to their essential minerals during the process of surface-weathering. For instance, soils immediately overlying granite may be expected to yield accessory minerals, *ceteris paribus*, common to that rock. A volcanic rock rich in pyroxenes, for example, may be expected to give rise to a soil in which this family is represented by at least one or two species. Where metamorphic rocks are engendered, many unusual minerals may be anticipated, *e.g.*, sillimanite, kyanite, andalusite, in addition to the usual rock-forming minerals.

Sediments, whether of geological age or constituents of drift, tend to yield far less variety of heavy mineral to soils than is the case with

igneous rocks, owing to the fact that the soil in this case receives its components second-hand; only the stable minerals survive this re-formation.

Where transported soils are involved, the mineral composition may be marked in its richness of species and their individual abundance or, by contrast, by impoverishment of species and infrequency of occurrence. In these types nothing goes by analogy, everything depends on the proximity of the source of supply of materials and on the nature of the soil environment in its ability to preserve original minerals or to determine their decomposition into some less definite product.

Most books and papers dealing with soil mineralogy stress the presence of the "mineral silicates" as they are termed by pedologists. These silicates are admittedly of supreme chemical importance; in fact they undoubtedly give character to the soil in which they occur, and their significance in the formation of the colloidal clay has already been noticed. But in terms of actual mineralogy, they are on the whole unsatisfactory, as with few exceptions, no definite minerals can be assigned to their varied formulæ assumed in chemical analysis. In so far as salts of different silicic acids are concerned, the problem is not so complicated, but it is chiefly in connexion with the alumino-silicate compounds, whose varieties and formulæ are numerous, that difficulty arises in interpreting them mineralogically. This problem merely recapitulates that faced in the study of clays, but at the same time it shows the need for more co-ordinated research between chemist and petrologist into these sediments.

It is, of course, not denied that the problem of the silicates in soils is complicated by the weathering factor which determines still further

change in these constituents, largely in response to climatic conditions. For instance, decomposition may proceed in one direction under arid conditions, giving rise to particular products manifest in the soil, and in a totally different direction, with correspondingly diverse results in soil-characters, under humid conditions.

The foregoing facts merely serve to emphasize the importance of relying where possible on those mineral constituents of soils less susceptible to change with circumstance and more fundamentally reliable as indices both of the soil itself and of its origin. Only accessory minerals can claim such immunity and distinction, and, from first principles, if for no other reason, their significance in soils is full worthy of recognition and of further careful enquiry.

As affording some indication of the nature and variety of minerals found in soils, we cannot do better than quote the list published by W. H. Fry of the species determined during the course of considerable research by the U.S. Bureau of Soils into American deposits of this character:—¹

Quartz	Glaucophane	Olivine	Tourmaline
Orthoclase	Enstatite	Epidote	Rutile
Microcline	Hypersthene	Zoisite	Ilmenite
Albite	Diopside	Piedmontite	Titanite
Oligoclase	Augite	Kaolinite	Fluorite
Andesine	Diallage	Apatite	Staurolite
Labradorite	Calcite	(Glass)	Corundum
Anorthite	Dolomite	Sericite	Sillimanite
Muscovite	Chlorite	Limonite	Kyanite
Phlogopite	Topaz	Hæmatite	Andalusite
Biotite	Axinite	Magnetite	Pyrophyllite
Actinolite	Serpentine	Garnet	
Hornblende	Iddingsite	Zircon	

It will be noted that with only one or two exceptions, the minerals listed are familiar sedi-

¹ *Econ. Geol.*, xx., 1915, pp. 292-295, and references cited.

mentary rock minerals; no specially uncommon species have been identified, though in environments to which exceptional parent-rocks have contributed material, many other minerals could be imagined, and have, in point of fact, been identified; this possibility is exemplified by soils in the neighbourhood of particular volcanic rocks or of outcropping metalliferous lodes, etc.

To the above list may be added the following minerals noted from the author's observations of various British and foreign soils:—

Anatase	Glauconite	Marcasite	Monazite
Barite	Gypsum	Pyrite	Siderite
Chalcedony	Leucoxene	Pyrrhotite	Sphalerite

Exceptional and localized species include:—

Misspickel	Galena	Malachite
Gold	Chrysoberyl	Azurite
Molybdenite	Cassiterite	Wolframite

Prof. J. Van Baren in his recent researches on limestone soils from the East Indian Archipelago¹ finds the following species in addition to many of those cited above:—

Amblygonite	Eukolite (?)	Copper	Vivianite
Chialstolite	Graphite	Tremolite	[Asphalt]
Cordierite	Heulandite	Turquoise	[Volcanic Ash and Glass]

Doubtless more extended observations will reveal the presence of many other interesting minerals in soils to swell the above lists.

The above selections are sufficient to emphasize the essentially varied character of the soil minerals, though it must be recognized that in so far as relative frequency of occurrence is concerned, there are striking contrasts, as is found

¹ *Communications Geol. Inst. Agric. Univ. Wageningen*, 1928, No. xiv. (This is in English and is one of the best contributions to the detailed mineralogy of soils yet published).

in the case of ordinary sedimentary rocks; further, as already stated, in a majority of soils, particularly in what may be termed "sedimentary regions," only the common stable minerals may be expected to characterize the relevant superficial deposits.

It must be emphasized that mere lists of minerals seldom convey much in themselves, as is the case in other petrographical work. To be of any value at all in soil analysis, the various species reported must be subject to interpretation in terms of local geology or conditions of soil formation. Any deductions based on the prevalence of a particular mineral suite in a soil should always take into account the probable source of origin of that suite, and the special geochemical significance its presence implies (if any).

It is relevant to mention here that determination of many soil minerals is often rendered easier by employing refractive index (immersion) methods (p. 75), the favoured practice in the United States.

MECHANICAL ANALYSIS OF SOIL PARTICLES. The grading of sediments either by sieving or elutriation has already received discussion (Ch. V). In the mechanical analysis of soil particles, for various reasons, the principle of "falling velocities" is made use of by the majority of investigators, especially in this country. In its simplified and practical form this method of grading is known as the "subsidence method" or, as adapted by Robinson, the "pipette method." It was the method officially adopted in 1926 by the Agricultural Education Association.

The principle is illustrated by taking three ordinary gas cylinders (glass jars), filling them with water and suspending in each silt, fine silt

and clay respectively. In any given time, owing to the relatively larger size of the silt particles, a greater depth of clear water will be observed than in the case of the fine silt, while the clay suspension may hardly have cleared at all.

If now a suspension composed of all three grades, *i.e.*, essentially ordinary soil, is placed in one cylinder, at a given time there will be observed three more or less distinct zones of fluid charged with sediment: an upper or clay zone, a middle or clay and fine silt zone, and a bottom or clay, fine silt and silt zone.

By judicious use of a pipette three samples may be obtained, one from each zone. That from the bottom is a mixture of all grades present in the soil; that from the middle zone is made up of medium sized and small particles; the third and top sample is composed of fine clay particles only. Thus estimations of clay, fine silt and silt can be made.

It should be noted, however, that soil chemists and physicists employ a different convention for expressing grade-sizes from that of the petrologist (p. 108). In this, silt ranges from 0.040 mm. (max.) to 0.012 mm. (min.); fine silt ranges from 0.010 mm. (max.) to 0.002 mm. (min.); clay thus has an upper limit of 0.002 mm., whereas in petrographic work the upper limit is chosen as 0.01 mm. For the grade-limits quoted, silt has a velocity range of 0.100 to 0.010 cms./sec., fine silt, 0.010 to 0.0001 cms./sec., and clay 0.0001 cms./sec. (N.B.—Logarithms of the falling velocity are conveniently employed instead of the velocity itself). Results are expressed either numerically or graphically.

In the case of sand particles occurring in the soil, coarse sand, 1.000 mm. (max.) to 0.200 mm.

(min.), and fine sand 0.200 mm. (max.) to 0.040 mm. (min.), these are removed, the latter by decantation, the former by sieving.

It will be apparent that where a number of analyses have to be carried out rapidly and with the minimum laboratory effort, the pipette method has much to commend it. On the other hand, in certain cases elutriation is preferable, particularly in coarse soils where the silt grades (petrological convention) are strongly in evidence, or where serial results are required between chosen grade-limits, this depending on carefully adjusted velocities of the upward current of water.

There are certain cases where both elutriation and sedimentation methods of mechanical analysis break down. One in particular has been described by B. de C. Marchand in connexion with the mechanical analysis of soils derived from basic igneous rocks such as norites.¹ These contain high proportions of magnetite which, together with other heavy minerals, makes up 39 per cent. of some of the samples. Such occurrences are, however, exceptional.

THE FUNCTION OF PETROLOGY IN SOIL STUDIES. It is, in conclusion, possible to sum up the potentialities of petrological investigations of soils, and at the same time indicate the most profitable lines of enquiry defined thereby:—

- (1) Determination of minerals present in soils and related deposits.
- (2) Elucidation of the genesis of soils from their accessory, often "heavy" mineral constituents.
- (3) Influence on soil characters of inherent minerals.

¹ *South African Journ. Sci.*, xviii., 1922, pp. 223-6.

- (4) Distinction between sedentary and transported soils, between drift and bedrock soils.
- (5) Correlation and differentiation of soils in a given region.
- (6) Relationship of particular soils to local geological conditions and peculiar rock-types.
- (7) Elucidation of the means by which certain needs of vegetable life are supplied in so far as those needs relate to inorganic (mineral) components of soils.
- (8) The solution of problems of soil contamination.
- (9) Determination of the nature and significance of soil-colouring matter.
- (10) Interpretation of mechanical analyses of soils according to the principles recognized in the case of other sedimentary deposits.
- (11) The pertinent aid of soil mineralogy in problems of classification and description.
- (12) Elucidation of various fundamental changes taking place in soil environments in different climatic conditions, where such changes are directly or indirectly attributable to the presence of certain unstable minerals.

The following is a selected bibliography of modern literature having reference to the particular phases of pedology discussed in this chapter:—

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APPENDIX I.

DETRITAL MINERAL DETERMINATION TABLES.

METHOD OF USE.

Tabular data of mineral determination usually imply the process of elimination for isolating a particular species according to the balance of positive over negative observations, and there are many mineral functions which may be selected as a primary basis of such differentiation. But permutations of minerals are many, and possible variations of colour, form, physical and optical properties for one and the same mineral so great, that no system, however comprehensive, can be designed to meet all cases. This is specially emphasized with detrital modifications of minerals, so that at the outset it is only claimed for the following tables that they *may* aid diagnosis of unknown grains; they must not be regarded as infallible.

A retrospect of detrital mineral analysis convinces the author that fundamentally colour, behaviour with polarised light, and relief, individually or collectively influence the first impression of specific identity conveyed to the mind; hence these properties tend to constitute the main criteria of recognition of species; crystal form, if preserved, even partially, is invaluable, but the chances of this are doubtful, the average grain possessing accidental shape, the product of a com-

bination of circumstances. Consequently the basis of the following tables is :

- (i) the initial observation of opacity or transparency and translucency;
- (ii) the behaviour of the mineral with polarised light, hence the division of isotropic from anisotropic species;
- (iii) the differentiation of such anisotropic minerals firstly by colour, secondly by apparent mean refractive index, thirdly by optical behaviour, more particularly extinction directions as suggestive of system of crystallization, corresponding optic axial character, pleochroism, and optic sign (if this can be determined).

Three different examples will suffice to illustrate the method of working with these tables :

(a) *Glauconite*. The grain as first observed under the microscope by transmitted light is seen to be black, *i.e.*, opaque. Table I is accordingly sought, the mineral examined by incident light, when its green colour is discerned; the left-hand column of the table under "green" suggests, by reading horizontally to the right, the possible shades of colour which may be developed, and ultimately the identity of the mineral itself established.

(b) *Ceylonite*. The grain as first observed under the microscope is green in colour and possesses high relief. It is found to be isotropic. Before proceeding further, it is tested for an interference figure since it may, perchance, be a basal section of a uniaxial mineral, not necessarily a cubic species. However, in the present instance no such figure is found, and consequently Table II is sought. Its green colour and high refractive index (when compared with Canada balsam) places it as one of the minerals in the bottom right-hand

group, *i.e.*, sphalerite, red spinel, ceylonite, chromite, picotite and garnet. Thus narrowed down, the identification of ceylonite is not difficult, since it is clearly not sphalerite or red spinel, it has not the character, dark colour or semi-metallic lustre of picotite (which as a transparent mineral is exceedingly rare in any case), and green garnet is scarce in detrital sediments; probably in the case of this particular mineral, its octahedral habit will confirm the diagnosis.

(c) *Epidote*. As first observed, it appears as a yellow-green grain possessing high relief and vivid birefringence colours. Either Table IV (yellow) or Table VII (green) may be consulted. Assume it to be the latter. Its refractive index being high, we look to the right-hand columns; if its orientation can be fixed, its oblique extinction (small angle) betrays its relationship to the monoclinic or triclinic systems, hence its biaxial character; this serves to narrow down the possibility to hornblende, tremolite, actinolite, epidote, monazite, augite, diopside, the only minerals with refractive indices >1.60 , possessing similar colour and oblique extinction; in this case, the extinction angle being very low, it is clearly not hornblende, tremolite, diopside, augite; hence actinolite, epidote and monazite remain. The first is rare in sediments, has a relatively low R.I., extinction angle up to 15° , and quite different form (fibrous) from epidote; monazite is so characteristic in shape and high refractive index, that it is soon ruled out (especially if tested with the spectroscopic eyepiece), that epidote alone remains as the strong probability. Confirmatory tests for figure (usually "compass-needle" type) and pleochroism (weak) serve to fix the diagnosis beyond doubt.

If the orientation of the grain cannot be determined in the first place, obviously the procedure in this instance is complicated, but an intelligent use of the full data of detrital minerals in the book in conjunction with these tables, will go far towards establishing identity in most cases.

Finally, it must be borne in mind that half the battle of detrital mineral diagnosis is won when the possibilities are narrowed down to a few species; this the tables will certainly accomplish; the rest will depend on individual ability and experience, or alternatively, on a careful and methodical use of the data given in this work.

TABLE I.
OPAQUE MINERALS.

Black by Transmitted Light.
Examine with Dark-ground Illumination.

<i>Colour</i>	<i>Shade</i>	<i>Mineral</i>
Grey	Lead-Grey Silver-Grey Steel-Grey, Purple-Grey, Crimson-Grey Dark Steel-Grey, Earthy Purple-Grey	Galena Magnetite Ilmenite Pyrolusite
Black	Dull or Soot-Black Black-Metallic, Brown on thin edge Black, Green-Brown on thin edge Resinous Black to Brown	Graphite Chromite Picotite Sphalerite
Brown	Rust-Brown	Limonite
Red	Red, Brick-Red	Hæmatite
Yellow	Brass-Yellow Pale Grey-Yellow Bronze-Metallic Bronze-Yellow	Pyrite Marcasite Bronzite Pyrrhotite
White	White White and Grey	Leucoxene Ilmenite with Leucoxene
Green	Green, Green-Brown	Glaucconite

TABLE II.
ISOTROPIC MINERALS.

The Mineral remains dark in all Orientations with Doubly Polarised Light, and yields no Interference Figure.†

	<i>Refractive Index</i>	
	Very Low ($n < 1.55$, R.I. of Canada Balsam)	Very High ($n > 1.70$)
COLOURLESS	Fluorite Opaline Silica	Spinel
COLOURED	Fluorite	Sphalerite Red Spinel Ceylonite Picotite Garnet Chromite

† N.B.—Basal sections of tetragonal, rhombohedral and hexagonal minerals will be isotropic with doubly polarised light : in which case a uniaxial interference figure should be obtainable, thus differentiating minerals belonging to these systems from the cubic species above. Certain varieties of chlorite often *appear* isotropic : p. 156.

TABLE III.

COLOURLESS ANISOTROPIC MINERALS.

The Mineral exhibits Interference Colours with Doubly Polarised Light. Uniaxial Varieties give Straight Extinction. Biaxial Varieties give Oblique or Straight Extinction.

	Mean Refractive Index			
	< 1.55	> 1.55 < 1.60	> 1.60 < 1.70	> 1.70
UNIAXIAL+	Quartz (ω) Chalcedony	Quartz (ϵ)		Zircon
UNIAXIAL—	Calcite (ϵ) Dolomite (ϵ)		Apatite Calcite (ω) Dolomite (ω) <i>Tourmaline</i>	Corundum
BIAXIAL+	Gypsum Plagioclase : Albite	Anhydrite	Barite Diopside Enstatite Sillimanite Topaz Zoisite Celestite Olivine	Clinozoisite Titanite (Sphene)
BIAXIAL—	Microcline Orthoclase Plagioclase : Anorthite	Kaolinite Lepidolite Muscovite Aragonite(α)	<i>Andalusite</i> Chiasolite† Tremolite Aragonite (β , γ) <i>Dumortierite</i> <i>Glaucophane</i> Axinite	Kyanite

† Crowded with black carbonaceous inclusions (p. 154).
N.B.—Pleochroic Minerals in *Italics*.

TABLE IV.

YELLOW ANISOTROPIC MINERALS.*

The Mineral exhibits Interference Colours with Doubly Polarised Light. Uniaxial Varieties give Straight Extinction. Biaxial Varieties give Oblique or Straight Extinction.

	Mean Refractive Index			
	< 1.55	> 1.55 < 1.60	> 1.60 < 1.70	> 1.70
UNIAXIAL+				<i>Rutile</i> <i>Xenotime</i> <i>Zircon</i> <i>Cassiterite</i>
UNIAXIAL—				<i>Anatase</i>
BIAXIAL+		<i>Serpentine</i>	<i>Enstatite</i> <i>Topaz</i> <i>Spodumene</i>	<i>Brookite</i> <i>Monazite</i> <i>Titanite</i> <i>Staurolite</i>
BIAXIAL—	<i>Cordierite</i>	<i>Kaolinite</i> <i>Lepidolite</i> <i>Muscovite</i> <i>Aragonite</i> (α)	<i>Actinolite</i> <i>Aragonite</i> (β , γ)	<i>Epidote</i> <i>Hypersthene</i>

* Yellow colour may be blended with green, brown or grey.
N.B.—Pleochroic Minerals in *Italics*.

TABLE V.

BROWN ANISOTROPIC MINERALS.*

The Mineral exhibits Interference Colours with Doubly Polarised Light. Uniaxial Varieties give Straight Extinction. Biaxial Varieties give Oblique or Straight Extinction.

	<i>Mean Refractive Index</i>			
	< 1.55	> 1.55 < 1.60	> 1.60 < 1.70	> 1.70
UNIAXIAL+				<i>Cassiterite</i> <i>Rutile</i> <i>Xenotime</i>
UNIAXIAL—	Dolomite (ϵ)		Dolomite (ω) <i>Tourmaline</i>	Anatase Corundum Siderite <i>Vesuvianite</i> ¶
BIAXIAL+			Olivine	Augite <i>Brookite</i> <i>Monazite</i> <i>Staurolite</i> <i>Titanite</i>
BIAXIAL—		<i>Biotite</i> Kaolinite	<i>Hornblende</i> Olivine	<i>Hypersthene</i>

* Brown colour may be blended with yellow or red.

¶ Vesuvianite may be positive (var. *Viluite*) or biaxial.

N.B.—Pleochroic Minerals in *Italics*.

TABLE VI.

PINK OR RED ANISOTROPIC MINERALS.*

The Mineral exhibits Interference Colours with Doubly Polarised Light. Uniaxial Varieties give Straight Extinction. Biaxial Varieties give Oblique or Straight Extinction.

	Mean Refractive Index				
	< 1.55	> 1.55 < 1.60	> 1.60 < 1.70	> 1.70	
UNIAXIAL+					<i>Cassiterite</i> <i>Rutile</i> <i>Zircon</i> (<i>Hyacinth</i>)
UNIAXIAL—			<i>Tourmaline</i> (rare)		<i>Corundum</i> (<i>Ruby</i>)
BIAXIAL+			<i>Zoisite</i> var. <i>Thulite</i>		
BIAXIAL—			<i>Andalusite</i> <i>Axinite</i>		

* Red colour may be blended with brown.

N.B.—Pleochroic Minerals in *Italics*.

TABLE VII.

GREEN ANISOTROPIC MINERALS.*

The Mineral exhibits Interference Colours with Doubly Polarised Light. Uniaxial Varieties give Straight Extinction. Biaxial Varieties give Oblique or Straight Extinction.

	<i>Mean Refractive Index</i>			
	< 1.55	> 1.55 < 1.60	> 1.60 < 1.70	> 1.70
UNIAXIAL+				Zircon
UNIAXIAL—			Apatite <i>Tourmaline</i>	Vesuvianite †
BIAXIAL+		Chlorite Serpentine var. Chrysotile	Diopside Olivine Sillimanite Zoisite <i>Spodumene</i> Enstatite	Augite <i>Chloritoid</i> Monazite
BIAXIAL—		<i>Biotite</i> Chlorite Serpentine var. Antigorite	<i>Actinolite</i> <i>Andalusite</i> <i>Dumortierite</i> <i>Hornblende</i> Olivine <i>Tremolite</i>	<i>Epidote</i> <i>Hypersthene</i>

* Colour varies from emerald green to dark green and olive, also blended with yellow and brown.

† Vesuvianite may be positive (var. Viluite) or biaxial.

N.B.—Pleochroic Minerals in *Italics*.

TABLE VIII.

BLUE ANISOTROPIC MINERALS.*

The Mineral exhibits Interference Colours with Doubly Polarised Light. Uniaxial Varieties give Straight Extinction
Biaxial Varieties give Oblique or Straight Extinction.

	<i>Mean Refractive Index</i>				
	< 1.55	> 1.55 < 1.60	> 1.60 < 1.70	> 1.70	
UNIAXIAL+					
UNIAXIAL-			<i>Tourmaline</i> §	Anatase Corundum (Sapphire)	
BIAXIAL+			Topaz Celestite	<i>Chloritoid</i>	
BIAXIAL-	<i>Cordierite</i>		<i>Dumortierite</i> <i>Glaucophane</i>	Kyanite	

* Colour blue to indigo-blue.

§ Often non-pleochroic.

N.B.—Pleochroic Minerals in *Italics*.

TABLE IX.
**MAUVE OR VIOLET
 ANISOTROPIC MINERALS.**

The Mineral exhibits Interference Colours with Doubly Polarised Light. Uniaxial Varieties give Straight Extinction. Biaxial Varieties give Oblique or Straight Extinction.

	<i>Mean Refractive Index.</i>				
	< 1.55	> 1.55 < 1.60	> 1.60 < 1.70	> 1.70	
UNIAXIAL+		Quartz (Amethyst)		Zircon	
UNIAXIAL—			<i>Tourmaline</i>	Anatase	
BIAXIAL+			<i>Spodumene</i>		
BIAXIAL—		Lepidolite	<i>Axinite</i> <i>Dumortierite</i> <i>Glaucophane</i> <i>Tremolite</i>		

N.B.—Pleochroic Minerals in *Italics*.

APPENDIX II.

LIST OF CERTAIN ROCK-FORMING MINERALS AS YET
UNRECORDED FROM DETRITAL SEDIMENTS (*excluding Recent deposits*), BUT TO BE ANTICIPATED AS
PETROGRAPHICAL RESEARCH PROCEEDS.

<i>Species.</i>	<i>Probable Mineral Association and Derivation.</i>
Chondrodite.	Olivine, amphibole, pyroxene, serpentine and other magnesian minerals; from crystalline limestones.
Datolite.	With secondary minerals, <i>e.g.</i> zeolites, or the products of erosion of basic igneous rocks.
Hussakite.	Zircon, xenotime, monazite, and rare-earths; from granite-pegmatite or gneiss.
Perovskite.	Titanium minerals; released by disintegration of certain basaltic rocks, <i>e.g.</i> , melilite and nepheline basalts.
Scapolite (Wernerite).	Garnet, diopside, titanite, apatite, zircon; from contact altered limestones.
Wollastonite.	Garnet, augite, diopside, calcite, epidote, zoisite; from contact-altered limestones and crystalline limestones.

Certain members of the Amphibole and Pyroxene groups, viz., *anthophyllite*, *barkevicite*, *arfvedsonite*, *riebeckite*, *æigmatite*, *hedenbergite*, *acmite*, and possibly *rhodonite* may also be contemplated.*

The Felspathoid and Zeolite minerals, on account of their inferior stability, can only be anticipated in exceptional local circumstances, and then only in Recent deposits.

* Some of these species have been recorded from Recent deposits.

APPENDIX III.

BIBLIOGRAPHY.

(See also *Addendum*, p. 502).

The following references to literature incorporate those published in the original volume and in the Supplement, with additions bringing the list up-to-date. This bibliography is not intended to be exhaustive, the titles being selected as far as possible to cover the various phases of petrographic work. The majority of entries concerns incoherent sediments; the consolidated rocks carry appropriate references under each heading (Ch. VII). Where titles appear in parentheses, the nature of relevant subject-matter is indicated instead of original heading; alternatively, short titles are in some cases given to save space. For a full bibliography of the science, consult the papers marked with an asterisk.

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Microscope Slides

to illustrate

“*SEDIMENTARY PETROGRAPHY*”

By

HENRY B. MILNER.

M.A., D.I.C., F.G.S., M.INST.P.T.

Microscope Slides of Detrital Minerals

to illustrate

"SEDIMENTARY PETROGRAPHY."

In illustration of the second (1929) edition of this work, an enlarged series of slides of minerals as listed below can now be obtained from the publishers. It need hardly be urged that competency in detrital mineral analysis comes only with constant practice with varied examples under the microscope, and the examples now available have been specially chosen by the author for students of this book and for others seeking to equip themselves with such practice. The mineral grains in these slides are carefully picked out by a geologist with special experience in detrital minerals. *Each slide contains only one mineral species.* Each mineral represented receives adequate discussion in the text and *as far as practicable the materials correspond in geological horizon and locality with those minerals illustrated in the work.*

The series is being increased from time to time, and in the case of minerals not mentioned in the list, special application should be made to the publishers as to the possibility of supplying them. Minerals which have been added to this list since June, 1928, are indicated by an asterisk. The prices of many of the slides have been modified and in several instances substantial reductions have been made.

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Andalusite ...	3 0	*Gypsum ...	3 6	*Rutile, yellow ...	3 6
*Anhydrite ...	3 0	Hæmatite ...	3 0	Serpentine ...	3 0
*Apatite ...	4 0	Hornblende ...	3 6	Siderite,	
Augite ...	3 0	Hypersthene ...	4 0	Spherulitic ...	3 0
Axinite ...	6 0	Ilmenite ...	3 0	*Sillimanite ...	6 0
Barite ...	3 0	Kyanite ...	3 6	Sphalerite ...	4 6
Biotite ...	3 0	Leucoxene ...	3 0	Staurolite ...	3 6
*Brookite ...	4 0	Limonite ...	3 0	*Titanite ...	3 6
Calcite ...	3 0	Magnetite ...	3 0	Topaz ...	5 0
Cassiterite ...	4 0	Microcline ...	3 0	Tourmaline,	
*Ceylonite ...	6 0	Monazite ...	3 0	brown ...	3 0
*Chlorite ...	3 0	Muscovite ...	3 0	*Tourmaline,	
Dolomite ...	3 6	*Orthoclase ...	3 6	blue (Indico-	
Enstatite ...	3 6	Olivine ...	5 0	lite) ...	4 0
Epidote ...	3 6	Pyrite ...	3 0	Zircon ...	3 0
Fluorite ...	3 0	Quartz,		*Zircon,	
Galena ...	3 0	rounded ...	3 0	purple ...	4 0
		Price for the whole set of 53 slides	£9 9s.		

Concentrates of Heavy Minerals from Various British Formations

to illustrate

“*SEDIMENTARY PETROGRAPHY.*”

Some of the Minerals in the slides are given in italics.

1. Recent Shore Sand, Yorkshire. (*Garnet, Ilmenite, Magnetite.*)
 2. Glacial Sand, Yorkshire. (*Barite, Pyrite, Apatite.*)
 3. Pliocene Sand, Cornwall. (*Andalusite, Tourmaline, Ilmenite, blue Anatase.*)
 4. Woolwich and Reading Sand (Eocene), Kent. (*Limonite, Kyanite, Hornblende.*)
 5. Thanet Sand (Eocene), Kent. (*Kyanite, Staurolite.*)
 6. Folkestone Sand (Lower Greensand), Surrey. (*Kyanite, Rutile, Zircon.*)
 7. Tunbridge Wells Sand (Wealden) Sussex. (*Zircon, Tourmaline, Rutile.*)
 8. Ashdown Sand (Wealden), Sussex. (*Zircon, Tourmaline, Muscovite.*)
 9. Portland Sand, Dorset. (*Dolomite, Kyanite, Tourmaline.*)
 10. Corallian Sandstone, Yorkshire. (*Zircon, Rutile, Garnet, Tourmaline.*)
 11. Lower Estuarine Sandstone, Yorkshire. (*Yellow Anatase, Leucoxene, Tourmaline.*)
 12. Middle Lias, Yorkshire. (*Zircon, Rutile, Limonite.*)
 13. Triassic Sandstone, Yorkshire. (*Apatite, Ilmenite, Zircon.*)
 14. Coal Measure Sandstone, Yorkshire. (*Garnet, Rutile, Dolomite.*)
 15. Millstone Grit, Yorkshire. (*Zircon, Rutile, Tourmaline, Monazite.*)
 16. Old Red Sandstone, Hereford. (*Garnet, Chlorite, Epidote.*)
 17. Cambrian, Co. Dublin or Wicklow. (*Leucoxene, colourless and purple Zircon.*)
 18. Torridon Sandstone, Scotland. (*Ilmenite, purple Zircon.*)
-

Price of Set of 18 slides £2 10s. od. Separate slides 3/- each.

THOMAS MURBY & Co., 1, FLEET LANE, LONDON, E.C.4.

Microscope Slides (Thin Sections)

to illustrate

"SEDIMENTARY PETROGRAPHY."

No.	Notation.	Type.	Formation, Locality, etc.
1.	A1. 1	Conglomerate.	Eocene, Hertfordshire Pudding Stone.
2.	A1. 2	Breccia.	Permian, Devonshire, or Eocene flint breccia, S. Hants.
3.	A2. 1	Sandstone.	Cambrian, Hollybush Sandstone, Malvern.
4.	A2. 1	do.	Old Red Sandstone, Westbury-on-Trym, Wilts.
5.	A2. 1	do.	Penrith Sandstone, Penrith, Cumberland.
6.	A2. 1	do.	Ightham Stone, Lower Greensand, Ightham, Kent.
7.	A2. 1	do.	Glaucinitic Sandstone, Upper Greensand, Dorset.
8.	A2. 1	do.	Teggs' Nose, nr. Macclesfield, Cheshire (with barite).
9.	A2. 2	Grit.	Millstone Grit, Dunford Bridge, Yorkshire.
10.	A2. 2	do.	Millstone Grit, Cullingsworth, nr. Bradford, Yorks.
11.	A2. 2	do.	Calcareous Grit, Lower Greensand, Faringdon, Berks.
12.	A2. 2	do.	Calcareous Grit, Tilgate Stone, Wealden, Sussex.
13.	A2. 3	Arkose.	Torridonian, Assynt, Sutherland, N.B.
14.	A2. 3	do.	Mount Tom, Mass., U.S.A.
15.	A2. 3	do.	Ardennes, France.
16.	A2. 4	Quartzite.	Pre-Cambrian, Ballachulish, N.B.
17.	A2. 4	do.	Cambrian, Hartshill, Nuneaton, Warwickshire.
18.	A2. 4	do.	Cambrian, Malvern (Malvern Quartzite).
19.	A2. 4	do.	Tertiary, Chateau de Fagnolle, Belgium.
20.	A2. 5	Ganister.	Coal Measures, Yorks.
21.	A2. 5	do.	Lower Coal Measures, nr. Bolton, Lancs.
22.	A2. 5	do.	Coal Measures, Derbyshire.
23.	A2. 6	Greywacke.	Ladock, Cornwall.
24.	A2. 6	do.	Old Red Sandstone, Herefordshire.
25.	A2. 7	Siltstone.	Ashdown Sand, Sussex.
26.	A2. 7	do.	Wadhurst Clay Siltstone, Sussex
27.	A3. 1	Clay.	Fairlight Clay, Sussex.
28.	A3. 1	do.	Gault Clay, Surrey.
29.	A3. 2	Fireclay.	Coal Measures, Stockingford, Warwickshire.

No.	Notation.	Type.	Formation, Locality, etc.
30.	A3. 2	Fireclay.	Coal Measures, Corbridge-on-Tyne, Northumberland.
31.	A3. 3	Fuller's Earth.	Nutfield, Surrey.
32.	A3. 4	Loess.	Rhine.
33.	A3. 7	Bauxite.	France.
34.	A3. 7	China Clay.	Cornwall.
35.	A3. 7	Laterite.	India.
36.	A3. 8	Mudstone.	Graptolitic Mudstone, Welsh Borders.
37.	A3. 8	do.	Liassic, West Bay, Dorset.
38.	A3. 9	Shale.	Monterey Shale (Miocene), Los Angeles, Calif., U.S.A.
39.	A3. 9	do.	Liassic Shale, Lyme Regis, Dorset.
40.	A3. 9	do.	Kimmeridge Shale, Dorset (parallel to bedding).
41.	A3. 9	do.	Kimmeridge Shale, Dorset (transverse to bedding).
42.	AB. 1	Marl.	Chloritic Marl, Dorset.
43.	AB. 2	Calc. Shale.	Purbeck, Dorset.
44.	B1. 1	Limestone.	Durness Limestone (Cambrian), Skye, N.B.
45.	B1. 1	do.	Coniston Limestone, Lake District, Cumberland.
46.	B1. 1	do.	Silurian Limestone (Coral), Wenlock, Salop.
47.	B1. 1	do.	Upper Silurian Limestone, Hather-ton Mine, Walsall.
48.	B1. 1	do.	Devonian Limestone, Lunnaton Qy., Torquay.
49.	B1. 1	do.	Carboniferous Limestone, Castle-ton, Derbyshire.
50.	B1. 1	do.	Carboniferous Limestone, Castle-ton, Derbyshire (encrinital).
51.	B1. 1	do.	Spirobis Limestone, Blackband Series, N. Staffs.
52.	B1. 1	do.	Ostracod Limestone, Upper Oolites, Yorkshire.
53.	B1. 1	do.	Liassic Limestone (Cement Stone), Barrow-on-Soar.
54.	B1. 1	do.	Portland Limestone, Dorset.
55.	B1. 1	do.	Purbeck Limestone (Shelly, "Purbeck Marble"), Dorset.
56.	B1. 1	do.	Foraminiferal Limestone, The Pyramids, Ghizeh, Egypt.
57.	B1. 1	do.	Crinoid Limestone, Matlock.
58.	B1. 1	do.	Stromatoporoid Limestone, Coombe Valley, Torquay.
59.	B1. 2	Dolomitic Ls.	Burlescombe, Somerset.
60.	B1. 2	do.	Magnesian Limestone, Durham.
61.	B1. 3	Oolitic Limes.	Inmosthay Qys., Bath.
62.	B1. 3	do.	Denbigh, Wales.

No.	Notation.	Type.	Formation, Locality, etc.
63.	B1. 3	Oolitic Limes.	Great Oolite, Bath.
64.	B1. 3	do.	Osmington Oolite (Corallian), Dorset.
65.	B1. 3	Pisolitic Ls.	Colwall Copse, Malvern Hills.
66.	B1. 3	do.	Pea Grit, Crickley Hill, Cheltenham.
67.	B1. 4	Globigerina Ooze.	Deep Sea.
68.	B1. 5	Chalk.	Beer Head, Devon.
69.	B1. 5	do.	Melbourne Rock, Middle Chalk, Cambridge or Surrey.
70.	B1. 5	do.	Flamborough Head, Yorks.
71.	B1. 5	do.	N. Ireland.
72.	B2. 1	Chert.	Radiolarian Chert, Mullion Is., Cornwall.
73.	B2. 1	do.	Portland Chert, Dorset.
74.	B2. 1	Flint.	Nr. Bridlington, Yorks.
75.	B2. 1	Silicified Ls.	Waterlip, Mendips.
76.	B2. 1	Spicular Chert.	Selsey, Chichester, Sussex.
77.	B2. 2	Siliceous Ooze.	Diatom Ooze, Deep Sea.
78.	B2. 2	Siliceous Earth.	Diatomite, Japan.
79.	B4. 2	Lignite.	Bovey Tracey, Devon, or Wealden, Sussex.
80.	B4. 3.	Coal.	Barnsley Seam, Yorks. (Parallel or transverse).
81.	B4. 3.	do.	Hard Mine, N. Staffs. (Parallel or transverse).
82.	B4. 3.	do.	Parrot Coal, Motherwell, N.B. (Parallel or transverse).
83.	B4. 3.	do.	Durain (Parallel or transverse to bedding).
84.	B4. 3.	do.	Clarain (Parallel or transverse to bedding).
85.	B4. 3.	do.	Vitrain (Parallel or transverse to bedding).
86.	B4. 3.	do.	Fusain (Parallel or transverse to bedding).
87.	B4. 4.	Torbanite.	Torbane Hill, Scotland (Parallel or transverse to bedding).
88.	B4. 5.	Oil-Shale.	Broxburn Shale, Scotland (Parallel or transverse to bedding).
89.	B4. 5.	do.	Kimmeridge Oil Shale, Dorset (Parallel or transverse to bedding).
90.	B4. 6	Asphalt.	Trinidad, B.W.I.
91.	B4. 6	Impregnated Sandst.	Tertiary, S.W. Angola.
92.	B4. 6	Impregnated Limest.	Gard or Seyssel, France.

No.	Notation.	Type.	Formation, Locality, etc.
93.	B5.	Phosphate.	Phosphate Nodule, Cambridge Greensand.
94.	C1. 1	Calcite.	Transverse section of stalactite.
95.	C1. 2	Dolomite.	New York.
96.	C2. 1	Bedded Iron Ore.	Northampton Ironstone.
97.	C2. 1	do.	Low Main Coal, Derbyshire.
98.	C2. 1	do.	Oolitic Ironstone, Claxby, Lincs.
99.	C2. 1	do.	Oolitic Ironstone, Westbury, Wilts.
100.	C2. 1	do.	Oolitic Ironstone, Abbotsbury Iron Ore, Dorset.
101.	C2. 1	do.	Cleveland Ironstone, Yorks.
102.	C4. 1	Rock-Salt.	Cheshire.
103.	C4. 2	Anhydrite.	Cumberland.
104.	C4. 2	do.	Nottinghamshire.
105.	C4. 2	Gypsum.	Nottinghamshire (Satin Spar).
106.	C4. 2	do.	Purbeck, Sussex.

Prices of MICROSCOPE SLIDES (Thin Sections)
to illustrate
"SEDIMENTARY PETROGRAPHY,"

By HENRY B. MILNER, M.A., D.I.C., F.G.S., M.INST. P.T.

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69	...	...	2/9	100	...	...	3/-
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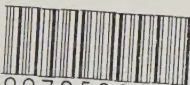
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